The effect upon UK energy supply schedules of the use of combined heat and power with district heating

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THE EFFECT UPON UK ENERGY SUPPLY SCHEDULES OF THE USE OF COMBINED HEAT AND POWER WITH DISTRICT HEATING

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ABSTRACT

The widescale use of combined heat and power with district heating will have a significant effect upon the quantities of primary and secondary fuels used in the United Kingdom. A new methodology for investigating the complex technological interactions between supplies and demands for fuels is developed, and the effect of sample CHP/dh scenarios calculated. Particular attention is paid to electricity generation to determine the impact of CHP/dh upon the operation of the merit order.

SYNOPSIS

Considerable work has been done on the potential role of CHP/dh in the United Kingdom (Chapter 1). However rather less is known about the effect of CHP/dh upon other fuels and energy technologies, which is difficult to assess because of the constraints which would operate upon CHP/dh technologies (Chapter 2). A wide range of energy supply and demand models have already been developed but are unsuitable for this study (Chapter 3) and in the light of these a novel type of model has been developed to examine this particular area (Chapter 4). Suitable data was collected and organised (Chapter 5) before undertaking a simplified pilot study (Chapter 6). The effects of CHP/dh upon the electricity supply system present particular problems which require special treatment (Chapter 7) to account for temporal effects and this is incorporated in a full scale study to determine the nature of the effects of CHP/dh upon the UK's energy supply schedules (Chapter 8). Further areas of study suggest themselves and are outlined (Chapter 9) and the conclusions of the study are listed (Chapter 10).

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Note on abbreviations

Throughout the thesis the following abbreviations have been used:

CHP combined heat and power

CHP/dh combined heat and power with district heating

HOB heat only boilers

HOB/dh heat only boilers with district heating

An index of notation is included in Appendix 11

Since the time of writing the District Heating Association (p30) has become the Combined Heat and Power Association.

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1. INTRODUCTION TO COMBINED HEAT AND POWER DISTRICT HEATING

The principal concern of this thesis is to identify some of the energy use implications of the use of combined heat and power technology for district heating in the UK. In particular, the thesis explores the constraints imposed by the technology on the energy supply industries, with special attention being given to the electricity supply industry.

It is thus appropriate to review the nature of the combined heat and power (CHP) technology in order that the source of the constraints be better understood.

1.1 COMBINED HEAT AND POWER TECHNOLOGY

It is a consequence of the second law of thermodynamics that when heat at an absolute temperature of T_1 is converted to work, the efficiency of the conversion is less than one and heat at some lower temperature, T_2, is also produced by the conversion process. The efficiency of a conversion process will always be less than $1 - T_2/T_1$, the theoretical maximum.

The combustion of fuel to produce electricity in a power station falls under the purview of the second law of thermodynamics. In other words the efficiency of the process is less than 100% and heat is rejected by the power station as a waste-product of the electricity production process. As power stations fall short of the theoretical ideal so their efficiency also falls short of the theoretical maximum efficiency and they typically have a heat to electricity conversion efficiency of between 25 and 35%.

However, reference to the ideal theoretical efficiency gives a useful pointer to improving the effeciency of the conversion process, since

$$\eta_{max} = 1 - \frac{T_2}{T_1},$$

the theoretical maximum can be increased by decreasing the temperature at which heat is rejected by the conversion process. The efficiency attainable by a power station responds in the same way and power station efficiency is increased by minimising the temperature at which the heat is rejected. In the case of steam power stations this is achieved by minimising the temperature at which the steam is condensed; in practice at between 30 and 35°C.

While power station design is very much concerned with maximising the efficiency of electricity production, combined heat and power technology addresses the problem in a different way. Rather than minimising the temperature at which steam condenses, steam is condensed at a temperature at which the cooling water may usefully be employed for some other purpose. For example, if the heat rejected from a power station is made available at 100°C it might then be used for industrial, commercial or domestic space heating, for industrial washing processes, or for domestic hot water supplies. In this case the heat by itself be regarded as a useful output from the power station and the power station as a combined heat and power station producing two products; electricity and heat.

Broadly speaking, the heat rejected from a power station is of limited usefulness if its temperature is less than 90°C. Since this is considerably higher than the 30°C normally encountered in a conventional power station, a loss of electricity output is the penalty for making heat available in this way. However, while the electricity production efficiency is decreased, the overall thermal efficiency is increased to as much as 75%.

Since electricity has a higher value than heat (both thermodynamically and economically) it is desirable that the quantity of electricity lost per unit of useful heat output gained, is kept as low as possible. This ratio is measured as the Z factor

$$Z = \frac{\text{electricity production lost}}{\text{heat output gained}}$$

Two bases of comparison may be used when calculating Z. Either, comparison may be based on the same steam conditions and flowrate at the turbine entry nozzle or comparison may be made on the basis of the same heat transfer rate to the steam. It is conventional to use the first of these two options but the author has found that the latter is useful when considering resource implications of, for example, burning 100 units of fuel in a conventional power station or in a CHP station. It will be stated clearly which basis is being used whenever the Z factor is used in this thesis.

Typical Z factors for steam plant may lie in the range 0.12 to 0.20 per unit of steam supplied to the turbine. For diesel and gas turbines the Z factor may be nearly zero. Numerical examples are given below.

Quantities of heat available, heat to power ratio, Z factor and overall thermal efficiency of CHP plant will depend upon the specific technology employed. Technologies available are as diverse as those for electricity generation. These are reviewed below.

1.1.1 Back pressure turbines

Back pressure turbines (see figure 1.1) represent the simplest conceptual development of the steam cycle used to generate electricity for public supply. (The author has written of this elsewhere, 1.1). The back pressure turbine is operated in such a way that steam is exhausted from the turbine at a pressure of say 100kPa rather than the more conventional 4kPa. At such a pressure heat is available at 100°C rather than 29°C available from the conventional low pressure condenser. Under these circumstances 200MW turbine plant might produce around 140MW of electricity and 330MW of heat at an overall thermal efficiency of 77% instead of 200MW of electricity. Heat and electrical outputs are determined by steam conditions and cycle design. A sample calculation is shown in Appendix 1. It is important to note that the higher the output temperature of the heat, the more electrical output is lost. It is thus important to ensure that heat is delivered at the minimum temperature that will assure its usefulness, in order to maximise electricity production.

Back pressure turbines are relatively inflexible in use. The heat to power ratio , R, is fixed for a given set of equipment. Thus it is not possible to use back pressure turbine sets to follow individually varying heat and electrical demand. For this reason the application for back pressure turbines is confined either to situations where heat and electricity demands are in constant ratio or where the plant can be used as baseload plant. Variation in total output can be achieved in the limits allowed by the turndown ratio of the plant but the heat to power ratio cannot. Variation of heat delivery rate can be achieved on a limited basis by heat storage. Limitations here arise from the practicability of storing low grade heat.

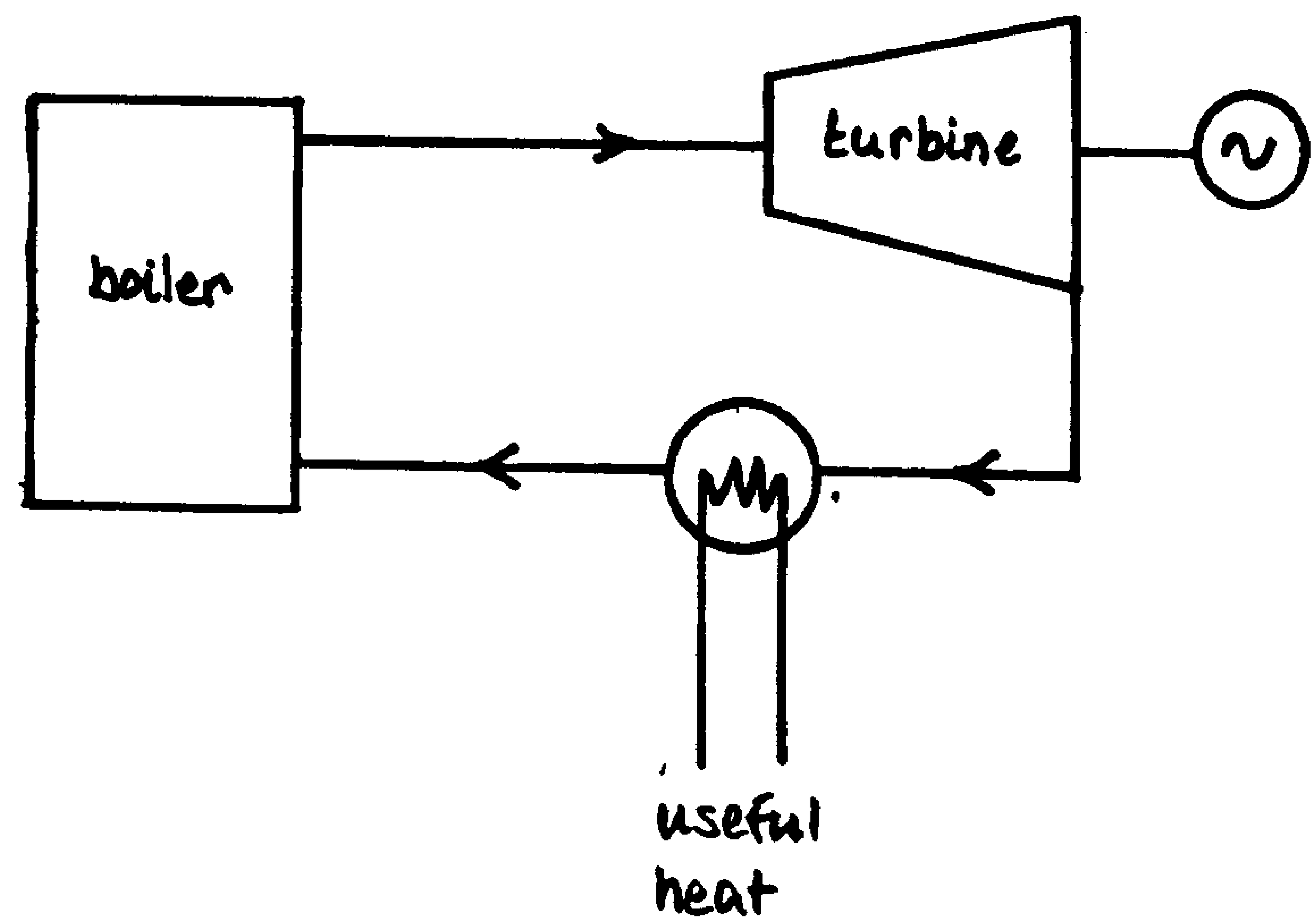

Figure 1.1 Back pressure turbine

The back pressure turbine has the advantage of cheapness since the expansion of the steam is small (for the example quoted above and used in Appendix 1, the steam volume increases 15.6 times compared with 350 times in the conventional power station) and hence the physical equipment is smaller. Further details of the practicalities of back pressure turbines may be found elsewhere (1.2).

1.1.2 Intermediate take off condensing turbines (ITOC's)*

Intermediate take off condensing turbines (see figure 1.2) are, in a sense, an intermediate between conventional power plant and the back pressure plant described above. A proportion y, of the steam flow entering the turbine is taken off at a pressure of between 0.5bar and 2.5bar and passed to a condenser where heat from the condensing stream is made available at between 80°C and 130°C. The remaining steam in the turbine (1 - y), is further expanded and then passed to a condenser in the normal way.

The advantage of this system is that y can be varied, with the consequence that the heat to power ratio may also be varied. The ITOC turbine is thus more flexible in meeting demand where the heat and electrical demands vary independently. In particular this feature makes the large ITOC turbine the most appropriate turbine for large scale district heating applications. However, the capital equipment cost of ITOC plant is comparatively high since low pressure turbine and condensing capacity, which is large and expensive must be provided for values of y approaching zero (ie conventional power station operation) but only partial utilisation of this capacity is possible since the plant will also be operated as CHP plant. The complexity of ITOC plant is also increased by the requirement to operate efficiently over a range of different flowrates, since equipment will rarely operate with its optimum flowrate. In general it is uneconomic to operate ITOC turbines

*Although likely to be a major component in CHP/dh systems in the UK, ITOC turbines are not considered in the study described in this thesis.

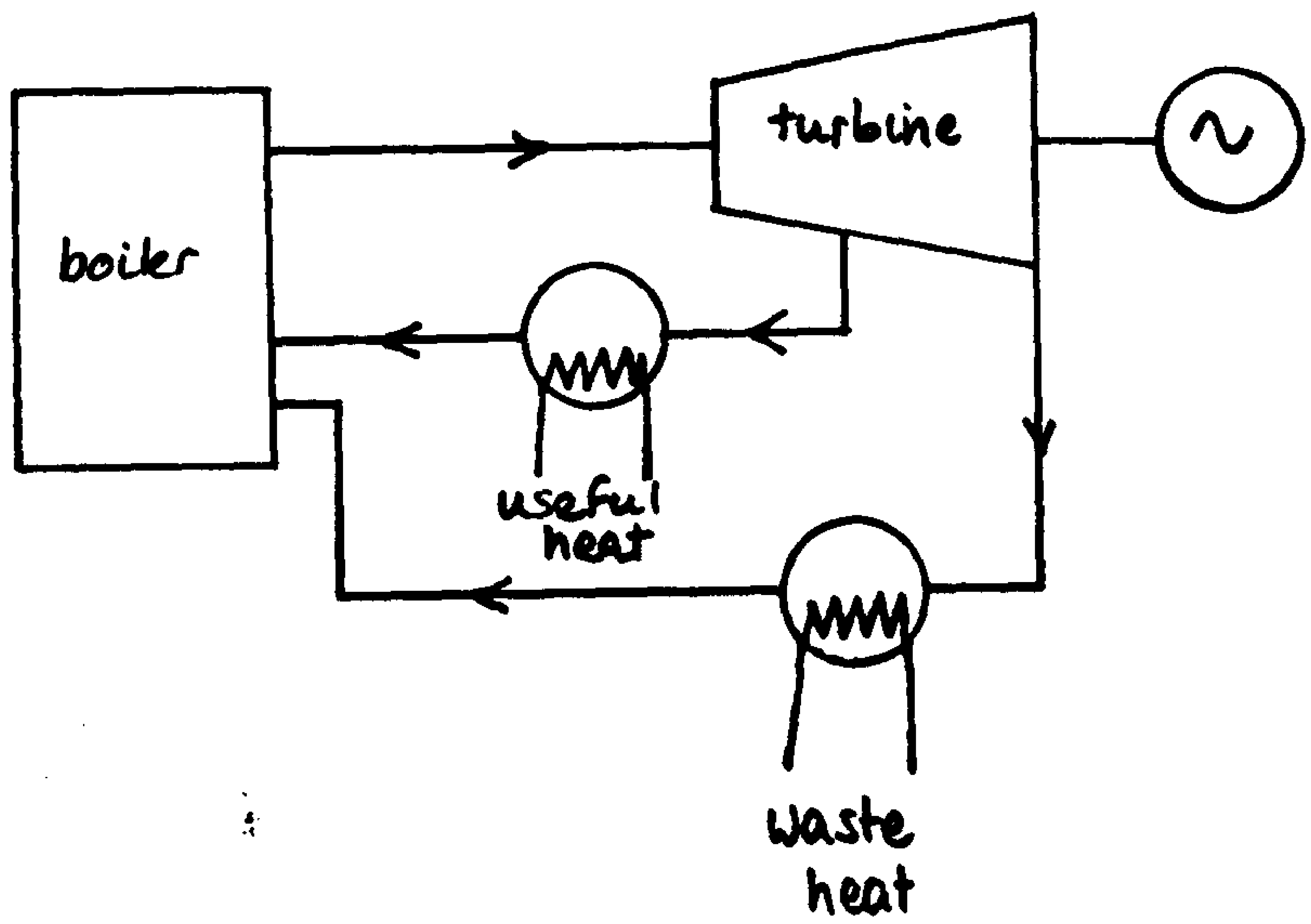

Figure 1.2 Intermediate take-off condensing turbine

in full condensing mode and performance is optimised by designing plant for a limited range of values for y. Further details and possibilities are discussed elsewhere (1.2). In this study, ITOC turbines will be attributed an average value for y and will be considered to have a constant value of R.

1.1.3 Gas turbine and diesel generators

Gas turbine power plant operates by exhausting the products of a high pressure combustion process through a rotating turbine to drive an electric generator. The gases leave the turbine at a temperature of approximately 4000°C, at which temperature they may be used to provide heat for a small steam turbine - the so-called combined cycle power plant. However gas turbine plant is frequently used by the UK's Electricity Supply Industry as peaking plant when it is run separately from steam plant. Even without heat recovery, the generation efficiency of gas turbine plant can be as high as 35%. It is possible to use the high temperature exhaust gases as a heat source with overall efficiencies of approximately 80%. The gas turbine offers the very considerable advantage as CHP plant of allowing heat to be made available at temperatures of as much as 150°C, which would be uneconomical for steam plant. In addition very little electrical generation efficiency is lost (ie Z is small). The cost per unit of electricity generated is however considerably higher than with equivalent steam plant and gas turbines are inflexible in operation since electrical efficiency falls off rapidly with load. In addition gas turbines require high quality fuel since the combustion products pass through the turbine itself. The vanadium and sodium salt content must therefore be very low. This compares unfavourably with steam plant which can, given appropriate burners, use more or less anything. Gas turbines are nonetheless well suited to peak load operation since they can be run up to full load in a very few minutes. As CHP plant, the principal advantage of gas turbine plant is the high temperature at which heat can be produced. Further details may be found elsewhere (1.3).

Diesel generators are based on diesel engines driving an electrical alternator. Water or an alternative coolant is circulated to keep the diesel engine from overheating. Temperatures available from this jacket cooling may go up to 200°C, depending upon the coolant flowrate. The heat to power ratio of such plant is primarily a characteristic of the diesel engine and is relatively independent of the temperature at which heat is made available since internal combustion engines are not limited by the Carnot efficiency (1.4). Any slight variation in electrical efficiency is as a result of the dependance of engine efficiency upon running efficiency. Typical values for R might be 1 for internal combustion engines with an overall efficiency of 70% (1.5). Suitable sizes of plant are discussed elsewhere (1.6, 1.7).

1.2 LARGE SCALE HEAT PRODUCTION

It is appropriate that while reviewing the CHP technologies, the technologies capable of supplying heat, in the appropriate temperature range, on a similar scale to the previously discussed CHP plant are also reviewed. Of these large scale heat production plant, only heat only boilers will be discussed further in this study.

1.2.1 Heat only boilers (HOB's) for district heating

Heat-only boilers are simply large boilers capable of delivering large quantities of heat at between 80°C and 150°C. They are principally used in conjunction with CHP plant to provide standby, back up, and supplementary heat. Since the HOB is by nature simpler than the CHP plant, it may be used for following heat demand. Any fuel may be used for HOB's although coal burning may only be possible where the boiler is sufficiently large to make exhaust gas cleaning and solid fuel handling economic.

1.2.2 Refuse incineration

The temperature and quantity of heat available depends upon the quality and quantity of refuse fed to the incinerator. Typical limits for economic operation of refuse burning boilers are a minimum heat output of 3MW and a maximum steam temperature of 450°C (1.7). This steam temperature would also allow the use of refuse incineration as a heat source for back pressure turbines (1.2). The quantity of heat available from refuse incineration cannot be varied on other than a short term basis (less than two days, say) since refuse supply is relatively invariant and refuse is not storable, both because of its volume and putrescibility. Experience of operating refuse plant as heat sources for district heating is already available in the UK. Such a scheme operates at Nottingham.

The Greater London Council's Edmonton incinerator raises steam to produce 150 MWh/year of electricity (which is sold to Eastern Electricity) by the combustion of 386 ktonnes of refuse annually. The revenue from electricity sales reduces the cost of incineration from £13.8/tonne to £10/tonne (1.54). There is considerable scope for and interest in the proposal that refuse incineration be linked to CHP/dh for the Isle of Dogs development in London. The economic advantages of building district heating into a development are enormous and taken together with the provision of heat for Tower Hamlets and Southwark the proposal has considerable advantages. (1.54, 1.55, 1.26).

1.2.3 Industrial waste heat

Sources of adequate size for district heating are most usually found in industries such as the steel and chemical industries. The supply of heat is constant and invariable, but may be totally absent when production ceases due to maintenance requirements. The value of the heat produced is low compared with the primary product so that the constraints of heat production are totally subservient to those of the principal product. An outline study for the use of waste heat from a steel works has been done (1.9) and it seems likely that the steel industry could be a major producer of heat (if it survives its present parlous state).

1.3 HEAT MARKETS

There are three ways of categorising the heat market available to heat producers, in particular those producing heat with combined heat and power plant. Markets may be categorised by temperature requirements, size and time characteristics. The markets described here are categorised by temperature requirement since this relates most directly to the way in which the supply technology operates.

1.3.1 Process heat

This category covers those heat demands requiring temperatures greater than 150°C, at which temperature heat is normally available as steam. The steam exhausted is fed directly to the site of requirement. The use of steam in this way normally limits the distance over which steam can be transmitted. Thus this effectively limits this type of use to industrial consumers operating their own electricity production plant.

1.3.2 Low grade heat

This category covers those markets requiring heat at temperatures which exceed those available from normal condensation operation but not exceeding 150°C and is the category most relevant to the subject of this thesis. Substantial quantities of energy in the UK energy economy are used to provide low grade heat for domestic, commercial, institutional and industrial premises, principally for space heating but also domestic hot water (DHW). The extent of this demand is enormous;

32% of delivered energy in the UK (1976) (1.10). This is approximately equal to the quantities of waste heat rejected by the UK stock of power stations. (1.11). The minimum temperature at which heat is useful for space heating and domestic hot water is 60°C. To allow for degradation in transmission and heat transfer, heat must be sent out from the producer at a temperature a few degrees above this. The further requirement that a realistic quantity of heat be delivered by a manageable quantity of water means that the economic send-out temperature lies between 85°C and 110°C.

1.3.3 Very low grade heat

There are uses that can be made of heat at between 20°C and 30°C. Typical large scale uses are in fish farming (1.12, 1.13 and 1.44) and in market gardening (1.45). Although the CEGB and Rank Hovis McDougall and Express Dairies partly operate fish farms and greenhouses at Drax, (1.45), it is unlikely that these activities will have a significant impact upon the UK energy supply schedule.

1.3.4 Time variation

Of particular relevance to the present study is the variation in demand for heat which occurs in a given period. Four characteristic time periods can be identified.

i) Effectively constant demand for heat can be found in light industrial situations where shift working is normal. Domestic hot water demand is also effectively constant throughout the year and the hot water tank effectively acts as buffer storage on a daily basis.

ii) Seasonal variations arise principally as a result of the variation in outdoor temperature and length of day. It is the major source of variation in domestic space heat demand and hence one of the major reasons for the large installed capacities of energy supply systems, and indeed of energy conversion equipment (eg domestic central heating equipment).

iii) Weekly variations in heat demand arise mainly as a result of the weekend effect. The weekend not only reduces demand for energy in the industrial and commercial sectors but replaces it by a qualitatively different spectrum of demand by increasing domestic demand over the two days involved. An additional effect is that of the Monday morning start-up. This surge in demand is due to the sustained demand to restore the environmental temperature which may have fallen during the weekend.

iv) Daily variation arises simply because of the way in which people use their homes and the way in which work patterns operate. Commercial and institutional (schools, government offices, etc.) premises may have fairly simple diurnal variations, reflecting the external temperature and solar incidence. Domestic premises show a much more complicated pattern of variation, the principal determinant of daily variation being occupancy rather than climatic variation. Some homes are heated all day, whereas in others heating may be limited to quite restricted periods during the evening. Some smoothing of demand occurs at the point of use due to the storage of heat in building fabric, or in hot water (DHW and 'wet' central heating) or in purpose built storage radiators.

Some time variation in demand may be eliminated by storage but is limited by the low storage densities of most materials.

It is important to realise that heat demand may vary quite independently from the demand for electricity and from the demand for fuels for non-heating purposes. This may prove to be problematic for the use of CHP technology to provide electricity and heat for district heating.

The four types of variation described above can each be divided into those demands which are predictable and those which are not. For example, in category (i) it is possible to know reasonably accurately several days in advance what the demand for heat will be. On the other hand, demand for heat in domestic premises cannot be predicted quite so accurately although experience and weather forecasting may allow a good estimate to be made.

1.4 CURRENT PRACTICE IN USE OF DISTRICT HEATING TECHNOLOGY

1.4.1 Europe

Even a cursory examination of the literature reveals that Europe has a much older tradition of district heating than the UK, much of it supplied with CHP-generated heat. In particular, Scandinavia has developed a widespread use of district heating based on local utility companies, a proportion from CHP stations. Much of the success of the Scandanavian district heating schemes arises from the organisation of energy supply in those countries. Being mostly local, the supply of heat can more easily be integrated into the local supply schedule. Central government plays little part in the setting up of schemes, except by cooperation with enabling legislation (1.14, 1.15, 1.16, 1.17).

Germany has sufficiently developed its district heating systems that it is now contemplating the construction of a National Heat Grid (1.18) to balance loads between cities and to make better use of installed boiler and CHP capacity.

The Soviet Union makes widespread use of district heating on all scales (1.19), from group heating of apartment blocks to large, city-wide district heating schemes. In this level of market penetration the centralised planning of both housing and utilities has undoubtedly helped. This factor has also enabled the rational use of industrial waste heat in local housing.

In France a total of 10,000MW of district heating capacity has been installed of which 2000MW are to be found in central Paris (1.19). Paris is unique in having the only steam distribution system in Europe.

Throughout Europe, one of the principal enabling factors in the penetration of district heating into the heating market is the ownership pattern and type of dwellings in European cities. Levels of home ownership are lower in almost all of Europe and the dominance of the British-style 'semi detached' is not found in most European countries where flat dwelling is much more the norm in cities (1.20). Thus a single agent controls and services a number of dwellings and is, in general, responsible for the provision of utilities which further facilitates take-up of district heating.

Undoubtedly a further factor encouraging the market penetration of CHP and district heating in both Scandinavia and France (though less so in Germany and the Soviet Union) has been their dependancy upon imported energy.

It is commonly supposed that district heating economics are favoured by the severity of Scandinavian winters and that the economics of UK systems might be less favourable. While colder winters might lead to larger per capita sales of heat than might be realised in the UK, the relative mildness of UK winters would require a smaller installed heating capacity with a consequence that plant load factors might actually be higher in the UK than is possible in Scandinavia.

It is also possible that the British tradition of austerity in home heating has prevented the development of district heating. Since a minimal standard of comfort can be achieved with a small heat source, it was not until after the second world war that domestic central heating systems began to be installed in homes as a matter of course. (1.20). Continental winters, on the other hand, mean that this level of provision has always been accepted as necessary. The widespread use of central heating with wet distribution systems (radiators) makes it very much easier to equip homes to use district heating, since installation of the appropriate domestic internals is unnecessary. (1.21).

1.4.2 United Kingdom

Until the last few years there had been almost no district heating within the United Kingdom. There have however been groups of houses usually of 50 to 100 in each group which had been provided with group heating systems. This occurred typically in developments of rental housing with a common landlord, typically a Local Authority. With the exception of homes in the Pimlico scheme (1.22) supplied by Battersea Power Station, none of these district heating schemes has been supplied by CHP plant. There are however, some larger district heating schemes. For example, the Nottingham City Centre scheme and that at Bretton, Peterborough (7000 and 3200 homes respectively) where heat is supplied to consumers through large networks. A comprehensive list of district heating schemes, serving both commercial and domestic consumers is to be found in the current DHA handbook (1.23).

Since the OPEC oil price rises of 1973 however, and even more so since the publication of Energy Paper 20, considerable interest has been evoked in all the district heating, CHP and total energy policies. While the interest has always been present in industry, this interest is now widespread amongst tenants' groups, conservationists and latterly local authorities. Interest by local authorities has been stimulated particularly by renewed awareness of urban poverty aggravated by the cost of domestic fuel (the phenomenon known as 'fuel poverty') and by a desire among Labour controlled local authorities to stimulate local economies by large scale public works of this type. (1.24, 1.25).

The 1977 White Paper 'Policy for the Inner Cities' (1.31) committed the Government to the maintenance of the social fabric of the inner cities and the desirability of district heating schemes is seen to be pertinent to this aim.

A wide range of feasibility studies has been undertaken. Notable among these is the report commissioned by the Department of Energy from W.S. Atkins Partners for a feasibility study for CHP district heating schemes in five major cities. This report was commissioned in response to the Department of Energy's own Energy Papers 20, 34 and 35 which had themselves stimulated much interested and enthusiastic debate while being rather cautious in their conclusions. When it was published in the autumn of 1982, the Atkins group reported (1.26) that for the nine cities they had studied, "schemes could provide heat at 10% below the cheapest alternative whilst showing rates of return about or above 5% per year as required of new investment by nationalised industries." (Executive summary). For each of the nine cities, selected by Atkins, (Belfast, Edinburgh, Glasgow, Leicester, Liverpool, London, Manchester, Sheffield and Tyneside), an area was selected in consultation with the local authority, potential heat loads were assessed and potential market penetration determined by survey. CHP/dh schemes were devised to meet the load. The connection of component parts of the project (heat mains, heat only boilers, CHP station) were to be phased so as to maximise early revenue and to delay capital investment in the coal-fired plant. In some cities the possible use of refuse incineration plant was incorporated into the feasibility study. Economic performance of each scheme was assessed under a number of assumptions by discounted cash flow analysis. The news that all the cities show a good rate of return is particularly interesting since the basic case adopted by Atkins was a 'worst case' analysis in which the prices of competing fuels were as cheap as was reasonable. The conclusions were found to be relatively insensitive to some important variables, including sales volume and capital expenditure taken both separately and together. The Atkins study estimated the UK's CHP/dh potential at 22,800MW (heat), somewhat less than that assumed by the Combined Heat and Power Group in Energy Paper 35. The Atkins study also looked at issues such as installation disturbance, consumer attitudes and environmental impact.

Government response to this report has so far been cautious (1.30). Other area feasibility studies have been undertaken, from the Pinkston study (1975-6) (1.27) which found under very pessimistic assumptions that there was no economic case for CHP district heating (the conclusions of this study have been shown by Lucas (1.38) to be of limited validity) to the more recent Southwark study (1981) (1.28) which was very much more optimistic about the prospects.

To conclude, it may be said that within the UK, the experience of using district heating schemes, while not widespread is growing, as is the size of schemes that the experience relates to. However, the experience of using heat from CHP plant in district heating schemes is limited to the Pimlico/Battersea scheme (which, while a technical success was a commercial 'albatross', 1.64). By contrast, the experience of producing feasibility studies is increasing rapidly. The higher level of interest and activity over recent years might be expected to lead to proposals being implemented at some stage in the future. However, considerable difficulties remain.

1.5 OBSTACLES TO CHP AND DISTRICT HEATING USE

1.5.1 Legislation and Institutions

The relevant Acts covering the production of heat in conjunction with electricity are the Public Utilities Street Works Act 1950 (1.29) which covers the 'digging up the streets' aspects of district heating installation and the Electricity Acts of 1947 and 1957 (1.41, 1.40). The Electricity Act of 1957 had the effect of bringing the CEGB and the Electricity Council into being and laid upon the industry the duties specified for the British Electricity Authority in the 1947 Act. Those duties relating to the present discussion are to 'promote the use of all economical methods of generating, transmitting and distributing electricity' (Section 1, Sub. 6(a)); to 'secure ..... (the) cheapening of supplies of electricity' (Section 1, Sub 6(b)) and to 'secure the combined revenues of the ..... Boards taken together are not less than sufficient to meet their combined outgoings properly chargeable to revenue account taking one year with another' (Section 36, Sub 1). This requirement has been taken to mean that the cost of supplying heat would have to be met entirely from revenue from sales of heat, including making good the lost revenue from lost electricity production. The stringency of this inferred requirement has meant that the CEGB is often cast in the role of 'wet-blanket', implacably opposed to CHP, whatever the demonstrable benefit. The 1967 Act makes it a duty of the Central Authority (now the CEGB and Electricity Council) to 'investigate methods' by which the heat from power stations (Section 50, Sub (1)) might be used for district heating or other purposes, although it has no positive power to impliment such district heating. The Area Boards do however, have the power to provide heating to buildings (Section 50, Sub (2)), together with the power to break up streets for such purposes (Section 50, Sub (3)). (1.50).

The recent Energy Bill includes a clause introduced as an amendment (1.42) which will replace Subsection (1) and (2) of Section 50 of the 1947 Electricity Act which will make it a duty of every Electricity Board to 'adopt and support' CHP schemes and district heating schemes using the heat derived from CHP plant. While this more positive legislation is to be welcomed, it by no means by-passes the financial obligation of the Electricity Supply Industry to meet its financial criteria in this connection as well as in its other areas of activity.

The evidence of the CEGB to the Sizewell 'B' Public Inquiry (1.43) may be adduced as evidence of the CEGB's attitude to combined heat and power. This states that the principal obstacle, as perceived by the Board, to the successful implimentation of CHP is the lack of a heat load of sufficient magnitude. (1.46). Significant economies of scale are to be gained (1.47) by using plant with capacity of at least 150-200 MWe (1.48) implying an associated heat load of between 280 and 370MW. The CEGB does not see as part of its role the distribution of heat generated in association with electricity and instead states 'that its proper role in relation to district heating would be as a bulk supplier of heat to district heating authorities. This would be analogous to its role as a bulk supplier of electricity to Area Boards.' (1.49).

In the light of these difficulties it is probably more helpful to see the CEGB, not as a wilful obstructor but as a cautious participator in what is currently viewed as an activity subsidiary to the main duties of the Board.

Meanwhile, it is difficult to assess precisely the extent to which the current legislation really does inhibit the CEGB's attitude to CHP.

1.5.2 Housing types

Energy Paper 20 (1.19) showed quite clearly the importance of housing density to the economic viability of district heating schemes. Housing density is obviously a highly variable quantity in the UK with the high density areas of the city centres showing a continuing decline as populations move to the less, but increasingly dense, suburban fringes (1.31). The suburban pattern of land use means that not only is the overall housing density reduced but the advantages of the 'clustering' of demand that occurs in city centres are lost in the more evenly distributed suburban fringe.

Even now, only 35% of houses are equipped with the 'wet' central heating systems (1.32) that are most readily connected to district heating networks. The provision of suitable house internals is a further cost item for the potential district heating programme, explicitly recognised by Energy Papers 20 and 35.

1.5.3 Cost of alternative fuels

Although the prices of fuels have risen by 30% (in 1982) relative to other goods since 1974 (1.37), the proportion of consumers' expenditure which is devoted to fuel and light has fallen steadily during the same period (1.34) from 4.5% to 4.3% as it has during the entire post war period. For this reason, there is as yet comparatively little market pressure for the introduction of district heating into the fuels market place. However it can be shown (1.33) that the presence of North Sea gas in the market place has done much to keep average fuel price low (the relative price of gas in 1982 was 10% lower than in 1974). A rise in the relative price of gas as a result of declining reserves is likely to have a dramatic effect on the average cost of domestic fuels and might be expected to stimulate consumer interest in alternative sources of domestic heating.

1.5.4 Cost of capital and test discount rate

Because the capital cost component of any district heating/combined heat is large, the criterion of meeting a specified test discount is a particularly stringent one in determining cost effectiveness of CHP projects. However since the Treasury's test discount rate for Nationalised Industries was reduced from 10% to 5% in 1977 (1.65), the prospects for CHP look substantially better than when Energy Paper 20 was published, with its sample calculations based on TDR's of 15, 10 and 5 per cent.

1.5.5 Power station siting policy

Power station site requirements are similar to those for any factory; in this case

(a) availability and accessibility of fuel supplies

(b) access to National Grid

(c) labour supply

(d) means of disposal for waste products (ash, flue gases and most particularly in this case waste heat, usually water-borne)

The size of the power station will determine the extent to which these requirements intrude upon the local environment. The large modern power stations have, of necessity, been sited away from the centres of population or, less often, in areas of major industrial development (for example, Fawley). The general desirability of siting power stations away from the main centres of population has meant that the construction of the large modern stations has displaced from service many of the older stations which are smaller and sited in urban centres. The loss of these urban sites is to be regretted since in many cases their location, their infrastructure (rail links, transmission lines), and the complement of trained personnel would make them attractive as sites for district heating boilers or CHP stations. Further details of siting requirements of power stations, most of which would apply to large CHP stations can be found in 'Modern Power Station Practice' (1.35).

1.6 CURRENT ATTITUDES

This section is a brief review of the attitudes of various bodies towards CHP and district heating technology and of the main issues and arguments that surround the area. Many of the issues are laid out in general terms by the author in 'Living with Technology' (1.36).

1.6.1 Department of Energy

Much of Central Government's energy policy and hence the research priorities of the D.En. is directed at energy supply rather than at modifying demand.

The two principal objectives of energy policy has been to ensure 'adequate and economic energy supplies' and that these should be secured at 'the lowest practical cost to the nation'. (1.59). In pursuance of these objectives the Department wishes 'over the next 20 years to see this nation's energy resources base more diversified and flexible to give us a national security of supply'. Consumer sovereignty has always been regarded as paramount and deliberate restriction of consumer demand an excluded possibility.

Coupled to this 'ground-rule' has been a progressive weakening of the Department of Energy under the present Government in line with that Government's preference for a reduction of the role of the State and State Monopolies in energy matters - exemplified by the breaking of the

CEGB's monopoly in the Energy Bill (1.50).

The Department's attitude to CHP is complex but at its simplest level, the expectation from CHP is not large, providing only 2% of domestic energy consumption (1.60).

Of relevance to the present discussion was the initiation under the Government of 1974, of the combined Heat and Power Group (the 'Marshall Committee') whose investigation of the prospects for CHP/dh in the UK resulted first in a preliminary publication, Energy Paper 20 (1.19) in April 1978 and then later, Energy Paper 35 (1.51). These two papers are probably the most far-reaching policy-oriented appraisal of CHP/dh ever done. They are the result of a general study of the cost-effectiveness of CHP and of its potential contribution. The cost effectiveness of CHP/dh was assessed against a number of alternative options and under a number of different assumptions about fuel prices, housing density etc.

The principal conclusion arising from this study was that, assuming a potential penetration of 30% into the low grade heat market, a saving of 20mtce/annum could be achieved by a technology which is already well proven and widespread abroad. A reduction in the test discount rate from 10% to 5% accompanied by an increase in the real price of fuels would give CHP/dh economic advantages over competing options (subsequent developments, reflected in the Atkins study bear this out). In the longer term (beyond 2000 AD), CHP would be in competition with synthetic natural gas heat pumps and electric space heating but it offers considerable energy saving advantages over these (7-30 mtce). An early start is essential if CHP/dh is to make any substantial contribution to future supply schedules. A suitable organisation is needed to coordinate activities.

Energy Paper 20 confined its attention to the use of heat distributed through district heating networks to commercial and domestic consumers and made only passing reference to industrial CHP generation for in-house consumption of electricity and heat. Energy Paper 20 was intended as a discussion document and was widely circulated with a view to stimulating this. Much discussion was indeed generated both with the Department of Energy and between other interested parties. One of its most important contributions to the debate was to stimulate interest and to provide a common basis for discussion and controversy. In addition to this, Energy Paper 20 was one of the first studies to talk in terms of a national programme of CHP implementation. Most previous studies centred around particular localities or had been of the non-specific advocacy type.

The approach adopted by Energy Paper 35 was substantially the same. It was produced as a result of the further deliberations of the Marshall Committee in the light of responses received to Energy Paper 20. The report was more detailed, paying greater attention to the politics of introducing CHP in the local situation and including an analysis of industrial CHP. Industrial CHP, the report concluded, should be encouraged by all concerned, in particular by the Gas and Electricity Industries who have the ability to impose punitive tariffs. The remaining conclusions stay substantially the same as in Energy Paper 20.

Energy Paper 20 had highlighted the importance of housing density in determining the cost of CHP schemes and as a consequence of this a sub-group of the Marshall Committee had been set up to investigate what actual heat demand densities might be in the United Kingdom. Energy Paper 34 (1.52), recording the results of this investigation, was published at the same time as Energy Paper 35. The report concentrated on the heat loads that might be available in 5 different cities.

1.6.2 Government and Parliamentary Responses

The Government attitude to CHP can be found in a lengthy written reply by John Moore, Under Secretary of State at the Department of Energy, to a parliamentary question from Peter Rost, MP for Derbyshire S.E. (1.53).

The primary concern of the Government is to ensure adequate and secure supplies of energy and to retain 'flexibility' on other energy options. While accepting that CHP/dh would lead to more efficient energy utilisation, the criterion of economic advantage must be met before decisions to proceed are taken. The disturbance involved in installing district heating is also of concern. The Government accepted that the Marshall Report was a generic study only and its recommendation that a programme of work be set up to determine the feasibility of CHP/dh in particular locations. This would give particular attention to the question of whether financial assistance would be required to enable CHP/dh to penetrate the low grade heat market.

The outcome of this is that the Department of Energy engaged W.S. Atkins and Partners to take a close look at a number of cities with a view to determining the feasibility of a CHP programme in each with the longer term objective of determining where a 'lead city' scheme should be initiated. Phase 1 of this study was published in July 1982 (1.26) (see section 1.4.2).

A recommendation of the Combined Heat and Power Group which was not accepted by the Government was that a National Heat Board be set up to coordinate district heating activities. The Government attitude to this is that the establishment of such a Board would be premature. This view, taken together with that of the Electricity Supply Industry, would suggest that the crucial actors in initiating CHP/dh schemes are likely to be local authorities and indeed there is considerable evidence to show that much of the initiative for CHP/dh implementation will come from this direction. This could be considerably aided by the Energy Bill legislation which will allow bodies outside the Electricity Supply Industry to generate electricity 'as a main business'. This would allow local authorities to enter into agreements with local suppliers of heat and electricity with a measure of independence from the CEGB. However, there is little evidence at the present time of the interest of companies in availing themselves of the opportunity to generate electricity in this way.

1.6.3 Local authorities

The publication of Energy Paper 20 and subsequent documents (Energy Papers 35, 34 and the Atkins report) have stimulated considerable interest in some Local Authorities, notably Labour controlled County Councils who see in CHP/dh the potential for dealing with chronic inner city fuel poverty and unemployment. Thus, following the publication of Energy Paper 35, several local authorities 'volunteered' to host the lead city programme. Notable among thse proposals were those from Newcastle (1.55) and Sheffield. The Greater London Council commissioned Orchard Partners (a notable group of consultants in the CHP/dh field) to prepare a study of the potential for CHP/dh in the London Borough of Southwark (1.28). This study led further into the GLC's Proof of Evidence to the Sizewell 'B' Inquiry (1.56) which seeks to show that the Sizewell B nuclear power station will be counter-productive in meeting the energy needs of Londoners. The case for CHP/dh is advanced as a counter proposal (1.37).

The developing interest by Local Authorities, some of whom already operate small district heating and/or group heating schemes in council developments, is likely to be of considerable importance since current attitudes suggest that they will be responsible to a large measure for implementation and administration of CHP/dh schemes.

1.6.4 Political groups

The attitudes of political parties, particularly those which have recent experience of government, is to some extent bound with recent experience of energy policy. The oil crisis of 1976 together with experience of industrial action by coal miners have engendered a wariness of heavy dependence upon a single source of fuel. District heating, as a single source of heating supply for perhaps a whole town might be seen as requiring the protection of a diversity of fuel supply. The penalty for this security would be the additional capital cost of stand-by plant with potentially low load factors and the 'doubling-up' of fuel delivery and storage systems at the district heating plant.

1.6.4.1 Conservative groups

The Conservative attitude to CHP/dh is reflected in the attitudes of the present Government. That is, that CHP/dh, while a good thing in itself, must show an economic rate of return and that the role of Government, once schemes are initiated, should be to allow CHP to take its place in the market without subsidy or preferential treatment.

1.6.4.2 Labour groups

The Labour party, at both national and local levels, has come to see CHP/dh as a key component in their energy programme. This is for reasons of employment creation potential, the attack on fuel poverty, preservation of the power plant industry as well as fuel efficiency (1.57).

1.6.4.3 Social Democratic and Liberal parties

The energy spokesman for the Liberal party has made his attitude to CHP/dh very clear and is, indeed, a staunch advocate of CHP/dh (eg 1.66).

1.6.5 Fuel Industries

1.6.5.1 The Electricity Industry

The attitude of the Electricity Supply Industry has been described elsewhere (section 1.5.1). It is worth noting that the attitude of the industry has been noticably warmer in recent years.

1.6.5.2 The Coal Industry

The coal industry would be less affected in the market place than other fuels since its market share for domestic and commercial space heating is less than one third (1.10). However, the principal customer of the industry is the Electricity Supply Industry and it is through this relationship that the Coal Industry derives its principal interest in CHP. The Coal industry could encourage the development of CHP/dh plant in the 50-200 MW(a) range since such plant would undoubtedly be coal fired. Neither NCB nor NUM have shown much enthusiasm in promoting coal-fired CHP plant.

1.6.5.3 The Gas Industry

The Gas Industry's response to the concept of CHP/dh, as voiced by the British Gas Corporation, can be seen quite clearly in the minority report of the gas industry's representative in the Combined Heat and Power Group. Dr. Clatworthy's report is attached to Energy Paper 35 and takes the line that the case for CHP/dh is by no means established and that substantial obstacles remain. The principal recommendations of this minority report should be the subject of a detailed and comprehensive evaluation. This study would be more detailed than that recommended by the majority report and would be a more wide ranging investigation of the energy needs of the locality. The prognosis from the BGC is that a more appropriate development in the medium term future would be the production of synthetic natural gas to be supplied through the existing gas supply system.

1.6.5.4 Oil Industry

The UK oil industry in 1981 supplied 4% of its output to the domestic sector (delivered energy basis; Digest of UK Energy Statistics) where it had a market share of 6%. Only 9% of UK refined oil output is used for electrcity generation; equivalent to an 8% market share. The oil industry does not therefore have a potentially strong interaction with any future CHP/dh programme.

1.6.6 Other groups

1.6.6.1 The District Heating Association

The District Heating Association is perhaps the most significant opinion holder and actor, outside the circles already described. The Association acts partly as a professional/industrial association for those involved in manufacturing and construction for district heating, and partly as a pressure group to encourage large scale commitment in the UK to district heating and in particular to CHP.

The DHA has been among the most active contributors to the debate following the publication of Energy Papers 20, 34 and 35. In particular its contribution has been in adding specific technical detail to the recommendations of Energy Paper 20. The forceful platform of the DHA is set out in the Association's handbook (1.23). Broadly speaking this platform is that CHP/dh should be adopted as a principal component of energy policy; the formation of a National Heat Corporation to implement CHP which would, in conjunction with a reformed electricity industry one of whose principal objectives would be to supply heat as well as electricity, divert additional central funds to implementation and research. The DHA has recently (1982/83) set up a liaison group to keep local authorities in touch with each other's activities in the area of CHP and district heating (1.63).

1.6.6.2 Academic research

Considerable academic effort has, in recent years, been directed at articulating the arguments for CHP, rather less against. Broadly speaking, the research falls into two categories; the investigation of local programmes in particular cities or factories, and on the other at the overall energy policy level, for example as parts of energy scenarios (1.62). Other research pertinent to this thesis will be referred to elsewhere.

2 CHP/dh AND OTHER FUELS

The purpose of this chapter is to set out the problem to which this thesis is addressed and to demonstrate that the subject area is potentially problematic. Reference will be made to some of the current thinking described in the previous section and, by using a number of simple calculations as illustration, the particular problems of the large-scale penetration into UK heat markets will be explained. The electricity and gas industries are shown to be two of the principal areas which will be affected by the introduction of CHP on a large scale.

Prior to the publication of Energy Paper 20, most discussion of CHP/dh in the UK was based around individual city or locality projects or was of the form of general 'campaigning' literature arguing for the adoption of CHP/dh, principally on the grounds of fuel savings (or, to be precise, as a means of obviating the troubling inefficiency of electricity production). Only limited attention was directed to the potential role of CHP/dh in an overall energy policy or to the impact that it might have upon the market shares of other fuels and upon overall energy demand.

However, without a detailed assessment of the actual demand potential for district heating, Energy Paper 20 took, as its basis for calculation, a market potential of 25% of domestic and commercial low grade heat demand after gas and oil are no longer available from the North Sea for heating. (The assessment of the actual demand potential was a task left to W.S. Atkins (2.1)). This level of market penetration was subsequently found by Atkins to be slightly over-optimistic.

It is clear that if a market penetration of this magnitude is contemplated, then there are likely to be major structural alterations in energy supply schedules. The interactions between fuels are complex. They compete for different markets and, perhaps more interestingly, oil and coal are inputs to electricity production. Combined heat and power is a curiosity among supply technologies since it produces two principal products rather than one;
expensive to store. (Oil refineries are another example, producing a number of principal products although here the problems are mitigated by the ability to store the products.) Thus, this particular technology will raise further complications since the two products are not produced independently.

Particular areas of ignorance become apparent when a large programme of CHP implementation is envisaged, since perturbations in national fuel supply schedules and fuel markets cannot be ignored when CHP/dh is practiced on this scale.

The magnitude of the impact of CHP/dh on the fuel markets can be inferred from the following illustrative calculation:

1977 domestic low grade heat demand (delivered basis)

= 69 GJ/household/year (Energy Paper 20, 2.2)

taking a figure of 19 million households in the UK, then

1977 national low grade heat demand

= 1311 PJ/year

1977 total national electricity demand

= 891 PJ/year (2.3)

An example CHP programme might supply 30% of domestic low grade heat demand. Assuming average heat to power ratio of 2 for the supplying CHP/dh plant, and ignoring delivered to useful energy conversion inefficiencies, then low grade heat supplied by CHP/dh plant

$$= 30\% \times 1131 \text{ PJ/year} = 393 \text{ PJ/year}$$

electricity supplied by CHP/dh plant

$$= \frac{393}{2} \text{ PJ/year} = 197 \text{ PJ/year}$$

proportion of electricity generated by CHP/year = 197 PJ/year

$$= \frac{197}{891} \times 100\% = 22\%$$

In other words, 22% of all the kilowatt hours of electricity generated within the UK, on these assumptions, would be generated in conjunction with heat. There are two further remarks to be made about this calculation which will be taken up later. Firstly, the achieved heat to power ratio of CHP/dh plant might be nearer to 4 than to 2, since in periods of peak heat demand, heat might be more economically supplied by heat only boilers taking up part of the load. This would reduce the proportion of electricity generated by the CHP plant. Secondly, the calculation shown above obscures the fact that neither heat demand nor electricity demand is steady throughout the year and that plant, some of it CHP plant, would have to be available to provide heat for distribution at the time of peak heat demand. Depending upon the proportion of peak load on the district heating system to be met by CHP plant, the proportion of electricity supplied will vary continuously throughout the year (with an annual average of 22%) with the implication that the proportion of generation capacity made up of CHP plant may be very different from 22%. It is one of the objectives of this thesis to illuminate this issue.

2.1 FUEL AND MARKET INTERACTIONS

Calculating the extent to which CHP/dh could change energy supply schedules is more complex than simply determining the present market share of each fuel in the low grade heat market and displacing an appropriate proportion by low grade heat produced at CHP/dh stations. This, taken together with the fuel input requirements of the district heating plant, constitutes the first order effects of district heating supply. Secondary effects are likely to be of particular significance since electricity has a substantial share of the low grade heat market. Thus, changes in the level of electricity demand would result not only in less electricity being sold but also in changes in the consumption of coal, oil and perhaps gas since these are inputs to the electricity production process. Were synthetic natural gas (SNG) ever to gain a substantial share of the low grade heat market a similar chain would occur since SNG is a secondary fuel.

CHP/dh introduces a still further complexity in the analysis of its implications since the supply of low grade heat from CHP stations will result in the production of electricity, with a consequent change in the level of output from conventional power stations and their input requirement, added to that of the reduction in the demand for electrical space and water heating. These interactions are illustrated by figure 2.1.

The foregoing indicates the need for a model of the interactions between energy suppliers and energy demands which can take into account the second and subsequent order effects of introducing a new energy supply technology. The development of such a model, the main task of the thesis project, is described in Chapters 4 and 7 and in the associated appendices. That supplies and markets must be considered <u>together</u> is illustrated by the example calculation presented in Appendix 2 which shows that when supplies and markets are considered together, a counter-intuitive effect is discovered. Appendix 2 is based on an article by the author (with D.G. Crabbe) first published in Electrical Review (2.4).

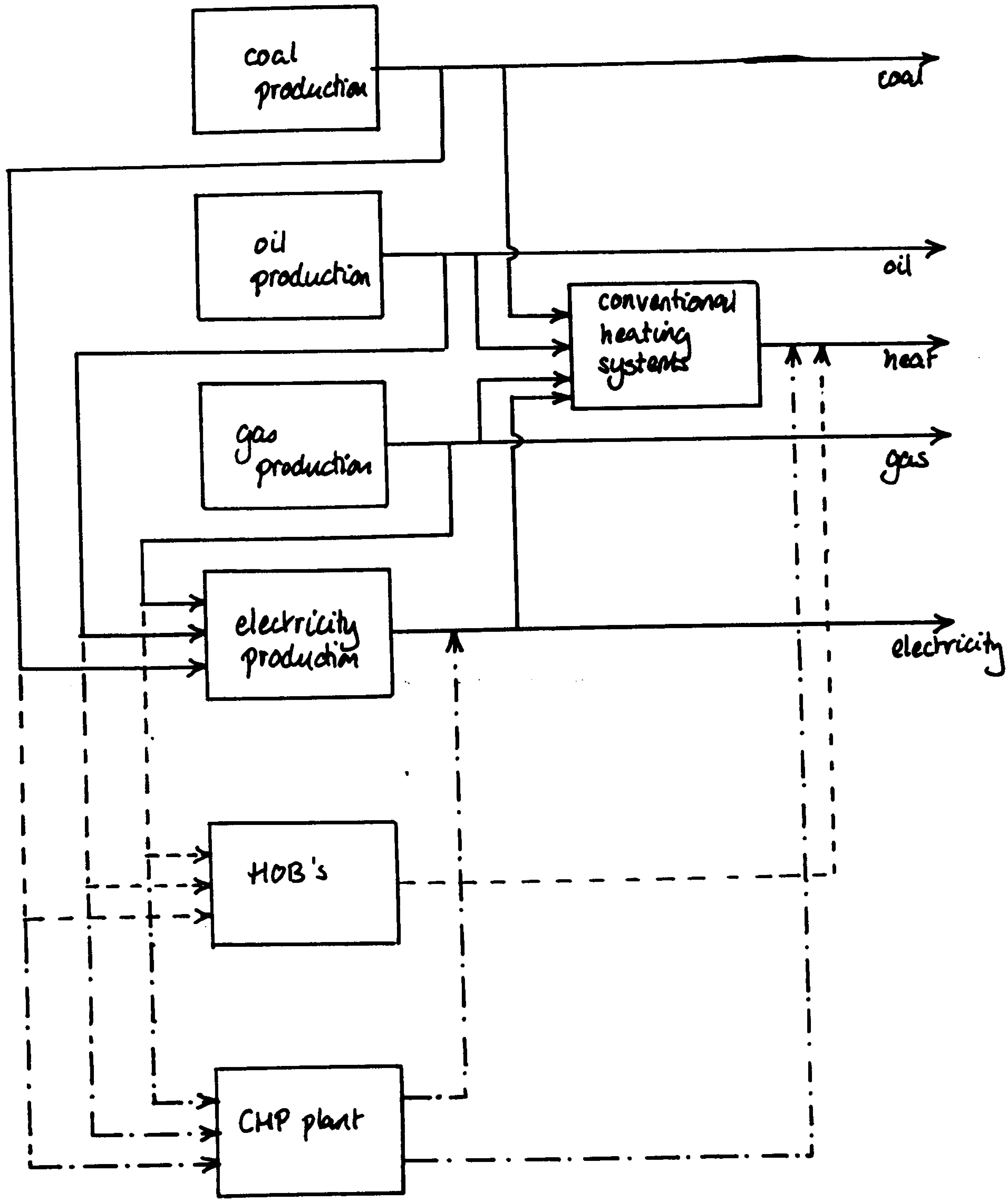

Figure 2.1 Energy system interactions

———— existing system

--------- system with heat only boilers

-·-·-·-·- system with combined heat and power

To summarise the examination of energy supply and energy demand together, taking into account the purposes for which fuels are used is an important background against which to determine the implications of CHP/dh for fuel supply schedules. This forms the first main area of this study.

2.2 TWO PRINCIPAL PRODUCTS

The production by a CHP plant of both heat and electricity, while offering the advantages of increased overall efficiency, raises a real difficulty since these two principal products are produced simultaneously. While scope for variation of the proportion is provided by ITOC turbines, the overall proportions of heat and electricity are constrained by the nature of the installed technology. For this reason, the scope for the penetration of CHP-derived district heating into the heat market will be limited by the saturation of either the available electricity market or the available heat market. The availability of the electricity and heat markets is limited by the high cost of electricity storage and by the size of the market networked to receive heat.

Also of concern is the way in which the heat demand and electricity demand vary with time. If the variation of the two demands means that at any point during the year the ratio of the two demands is not equal to the heat to power ratio of the CHP/dh (whether or not this includes a heat-only-boilers element), then there is a potential mismatch problem. An exploration of the mismatch problem forms the second main area of this thesis study, as detailed in the next section.

2.2.1 Low grade heat demand

Low grade heat demand is easy to understand, even if not to model or to predict. Low grade heat in the domestic and commercial sectors is used principally for the supply of domestic hot water and for space heating. While domestic hot water demand is effectively constant throughout the year, space heat demand is strongly influenced by three factors. On a yearly basis, demand is very seasonal, increased demand in the winter reflecting the colder external temperature. External temperature also leads to short term variations in demand when 'cold snaps' occur. Daily, and to a less extent weekly, variation in heat demand reflects building occupancy patterns, showing peaks in the morning when buildings are warmed up for the day and in the evenings. Other variation depends upon the time constants of the buildings to be heated, in effect the heat storage capacity of the buildings.

2.2.2 Electricity demand

Electricity demand, in the absence of district heating, shows variation (figure 2.2) which reflects the extent to which electricity is used for a wide variety of purposes not directly related to external temperature and it is likely that if the low grade heat demand, presently met by electricity, were met by an alternative, then the only seasonal effect left would be that arising from lighting demand and seasonal, behaviourally induced, load variation. (An example of the latter might be that of the low demand during the summer holiday period when many manufacturing enterprises close down completely.)

2.2.3 Mismatch

It is only possible to determine the extent of any mismatch by a detailed examination of the demands for both electricity and low grade heat and referring this to the capability of variation of the CHP/dh technology used to meet it.

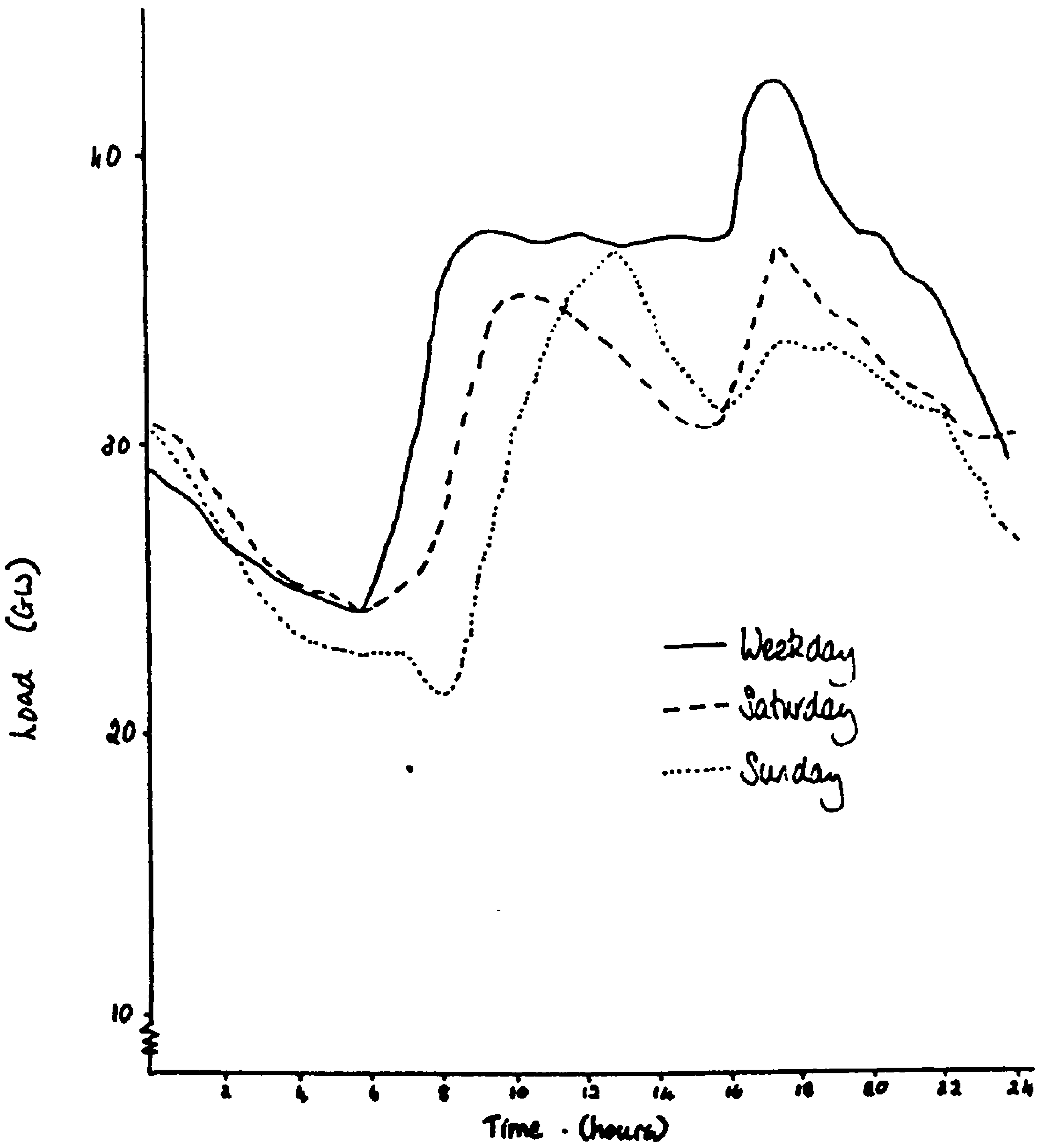

Figure 2.2 Typical winter daily electricity load curves

Source: CEGB (2.5)

If there is a significant mismatch between electricity and low grade heat demand, then there exist a number of approaches to alleviating them. These are storage and transport.

2.2.3.1 Energy storage

Electricity in the UK is supplied via the National Grid which connects all the points of supply and all the points of demand. Supply is matched to demand by switching power stations on and off. At any instant, the demand is met by the 'least cost' set of stations whose capacity totals to the instantaneous demand. To a first approximation, there is no geographical relationship between points of supply and demand. (Power stations may be switched on in 'out of merit' order if the distances between centres of supply and centres of demand would lead either to overload of transmission lines or to unacceptable transmission losses).

Within this context the only purpose of energy storage in which electricity is the input and the output is to allow electricity produced at times of low demand to be used at some later time. By this means the electricity available from the energy store, originally produced at low unit cost, may be used at times of peak demand instead of generating electricity at high unit cost. The pumped storage facility at Dinorwic will provide (potential) energy storage of approximately 8.4 GWh for an electricity input and output of 1.5 GW to add to the 1.1 GW already available to the UK Boards. The limited number of sites means that the capacity for balancing of electricity and heat demand by this type of storage is likely to be limited, despite its apparent economic attractions.

If it were possible to use hot water for energy storage and transport, without degradation in temperature, then CHP stations could operate as members of the merit order of power stations, producing hot water which could then be stored and transported to the point of demand. The position of each power station in the merit order would then be determined by its marginal cost of electricity in the normal way; the marginal cost being calculated by making due allowance for heat production. However, as will be shown below, hot water can neither be stored for long periods nor transported long distances without significant energy loss and hence temperature reduction and this implies considerable 'out of merit' running by CHP stations, with consequent displacement of normal power stations.

Variation in heat demand may be considered to occur in four characteristic ways. These are the daily cycle, the weekly cycle, the seasonal (yearly) cycle and the occurrance of 'cold snaps' which may occur during any season and are a significant departure from average heat demand for a period which may last between several days and several weeks. These variations in heat demand impose different requirements upon energy storage systems designed to be a buffer between heat supply and heat demand.

In practice, it has been shown in Sweden and elsewhere (2.6) that energy can be stored economically as sensible heat in reservoirs for several months. Both input and output are in the form of either hot air or hot water, the former allowing higher operating temperatures. Economic performance of sensible heat stores favours frequent cycling, which favours daily storage in large reservoirs which have high volume to surface ratios to minimise heat loss. Water offers considerable advantages over other materials for the storage of sensible heat. In the absense of widespread experience of large scale sensible heat storage, evidence presented by Flood (2.6) suggests that accommodation of the daily, weekly and 'cold snap' variations in heat demand might reasonably be expected to be feasible using sensible heat stores. Interseasonal variation would require developments in technology to include perhaps, thermochemical storage in which thermal input is converted to chemical energy for later delivery as a thermal output.

Any CHP or district heating scenario can assume a range of energy storage components ranging from interseasonal storage which would permit energy input at any period to be output at any subsequent period without any constraint upon either input or output rates through to the other extreme in which both electricity and heat supply must be strictly synchronised with demand ie no energy storage capability at all. A number of interesting and more credible storage scenarios exist within this range and are discussed in section 2.5 below. Ultimately the adoption of any scenario would be that of the optimum economic balance within a technologically feasible range.

2.2.3.2 Heat transmission

The flowrate of water required to transport a given quantity of energy as sensible heat depends upon the temperature at which the water is sent out and upon the minimum acceptable return temperature. The higher the send out temperature the higher the transmission energy losses but the lower the flowrate required for a given return temperature. The lower the flowrate, then the lower the pumping costs for a given diameter of pipeline. The larger the diameter of the pipeline then the less is the percentage energy loss since the surface to volume ratio decreases.

A more detailed analysis can be found in Energy Paper 20 (2.7). Pipeline losses and pumping losses mean that it is not possible to transport energy as sensible heat over long distances without substantial energy losses and that CHP stations might best supply local heat markets while feeding their electricity production into the National Grid.

Nonetheless a National Heat Grid is to be constructed in West Germany (2.8). The primary purpose here will be risk-sharing between sites rather than the operation of a 'merit-order' of heat sources. A similar Heat Grid, for whatever purpose, is unlikely to be replicated in the UK since it will be a very long time before district heating makes a substantial contribution to the UK energy supply schedule. The issues raised by the consideration of a national heat grid are not considered in this thesis.

2.3 CHP STATIONS AND THE MERIT ORDER

The above examination of the constraints operating upon a CHP station as a producer of both heat and electricity indicates that the most effective way of operating is by treating the two demands as being geographically quite distinct.

Since heat cannot be transported over long distances, the CHP station is constrained to supply the local heat demand, without the load sharing that would come with a hypothetical national heat grid. Electricity produced as a by-product is fed to the National Grid.

Almost all CHP proposals centred on particular localities have seen CHP production in this way. Heat is produced by a CHP station, usually in conjunction with heat only boilers, as the principal product. With the quantity of heat storage being determined by the economics of heat production, the plant is operated so as to meet and follow local heat demand. Electricity is seen as a by-product either to be used in-house (if the CHP/dh operator is a large-scale user of electricity) or to be 'dumped' into the National Grid. (The difficulty of making CHP/dh and industrial chp schemes economic has been found to depend strongly upon the rate at which the Electricity Supply Industry was prepared to pay for this electricity.) Evidence taken by the Select Committee on Energy showed that there is considerable feeling that the rates offered were inadequate or punitively low (2.9)). The quantity of electricity available from a CHP plant at any instant would depend, not upon demands placed upon it by the electricity supply system but upon local heat demand and the instantaneous heat to power ratio. CHP plant, whether operated by the Electricity Supply Industry or by other bodies, will therefore appear as intruders in the merit order, unconstrained by the normal merit order load sequencing "They will have to operate when they have to operate, and that is all there is to it" (2.11). The extent to which this will detract from the efficient operation of the merit order was previously unknown. It was the realisation that the damage to the operations of the merit order were potentially very significant that gave a major impetus to this project which has demonstrated that there is indeed cause for concern when district heating penetrates the low grade heat market to the extent envisaged in Energy Paper 20.

2.4 PROBLEMS TO BE INVESTIGATED

This thesis takes as its subject area the consequences of introducing, in the UK, a CHP/dh programme on a scale similar to that suggested by

Energy Paper 20. The problems addressed break down into two main categories

(1) Determination of the effect of displacing fuels from the low grade heat market with low grade heat generated by CHP/dh plant

(2) Investigation of the consequences of using a technology which produces two principal products when one principal product (heat) must be produced to meet a specified demand and when the non-principal product (electricity) is to be 'dumped' into an otherwise highly organised production system.

The questions to be answered can be summarised as follows:

(a) What are the quantities of each fuel that would be required in the UK for heating and other purposes under a number of different assumptions about CHP/dh implementation and a number of assumptions about other technologies (availability of North Sea Gas etc.)?

(b) To what extent will power stations in the merit order be displaced by any CHP/dh plant that is installed? How much electricity will be available to the grid and at what times? Which groups of power stations will have to operate at reduced (or increased(?)) load factors if electricity is dumped into the National Grid by CHP plant.

(c) To what extent are changes in the conventional electricity generation system attributable to (i) the displacement of electricity from the low grade heat market by district heating and (ii) the generation by CHP plant of electricity displacing conventional plant?

The purpose of this project is not to predict what CHP strategy will be adopted in the UK, nor to make presumptions about which strategies should be adopted. Instead a representative sample of a wide range of possible CHP 'scenarios' is examined with a view to increasing understanding of what the consequences of working towards particular scenarios might be.

A few of these issues were touched upon by the District Heating Association in their evidence to the Select Committee on Energy (2.10). This thesis gives numerical substance to the observations of the DHA and others.

2.5 MAJOR ASSUMPTIONS

As observed in section 2.2.3.1 above, the role of storage, in accumulators of sensible heat is likely to have a significant bearing upon the performance of any CHP/dh technology and is also likely to affect the answers to the questions posed in section 2.4. However, in the interests of simplicity and achieving the aims of the project it was found necessary to exclude exploration of the effects of different heat storage strategies.

The assumption has been made that adequate storage (of unspecified type or capacity) will be incorporated in any CHP/dh scenario to ensure that within each of the specified quarterly periods, heat demand can be met by heat produced during that quarter. This is equivalent to the assumption that daily, weekly and 'cold snap' variations in heat demand can be accommodated by storage but that no net transfer between seasons is possible.

This assumption has been made, not because it is in any sense a 'most likely' or 'best' use of storage but simply because within the context of the present project it struck the best balance between usefulness and convenience.

An explicit study of storage is not included in this thesis although possible approaches to such a study are discussed in section 9.3.1.2.

2.6 EXCLUDED AREAS OF STUDY

The methodology adopted in this study is developed in Chapter 4 and beyond but it is appropriate at this stage to make some reference to topics which will not be addressed.

Notably, prices, costs and economic issues are not explicity addressed. The reasons for this need careful explaining and proper recognition given to the importance of the excluded issues.

Economics and technology are very closely linked especially in areas such as energy use. Where a multiplicity of technologies exist to achieve a given aim, then conflicting advantages and disadvantages may be given economic values to arrive at an appropriate choice. What are perceived as technological constraints are very often in fact economic constraints and it may be that if enough money is devoted to the solution of a problem then it can be solved. The unwillingness to commit the resources results in the perception of a technological problem. Clearly our present understanding of science spells out a number of technological limitations that are not susceptible to economic pressure. For example, the second law of thermodynamics sets a technological limitation on energy conversion efficiency upon heat engines which is incapable of improvement no matter what the economic pressures*.

Within the context of the present study, the actual mix of home heating methods within any scenario would reflect relative prices of the fuels and their utilisation technologies much more than the nature of those technologies. However, the purpose of the study undertaken is aimed at furthering understanding of the effects of CHP/dh use rather

*Electricity generation need not, however, be forever constrained to the heat engines route. Fuel cells allow a theoretical efficiencies of 100%

than at accurate descriptions and enumeration of actual scenarios which might arise. At face value this task is impossibly large and must be taken a little at a time. The part of the task undertaken here is to understand what effects might arise as technological consequences of CHP/dh use. In reality these consequences will interact with economic consequences and the economic environment so that the actual outcome will reflect both features. But as explained more fully in Chapter 3, the actual outcome is of less interest and even with knowledge of economic effects would still be unpredictable, in the context of this study, than is the acquisition of an enhanced understanding.

No attempt is made to optimise to any particular objective any CHP/dh programme that might be adopted, whether on the basis of cost or of energy saving. However, the model developed to meet the objectives of the project has the potential to be developed into an optimising model by linear programming. This is more fully discussed in Chapter 9.

No attempt has been made to examine any geographically particular CHP/dh scheme. The project adopts the same type of generic approach as do Energy Papers 20 and 35.

The model developed to meet the project objectives has no predictive capability. The questions it can answer are of the "What would happen if ....?" type. The model is not dynamic although it can be used stepwise to give a semi-dynamic picture. It gives 'snap-shots' of particular hypothetical years for which some specified set of conditions pertains.

3. ENERGY MODELS FOR TECHNOLOGICAL CHANGE

The introduction of CHP/dh is an example of a technological change. Technological change as an economic, political and technological phenomenon has generated a hugh body of literature. In this Chapter, the nature of technological change is explored and the approaches that have been taken to examination of the impacts of technological change are examined.

This process of examination leads to discussion of some of the models of technological change and some serious shortcomings are identified, particularly in large models capable of dealing with a variety of technological changes. Recognition of these problems leads to a specification of some modelling objectives.

In this examination of possible approaches to modelling technological change, particular attention is paid to input output models since it was upon input-output analysis that the author's own model was eventually (and rather loosely) based. The analytical basis and the operation of input-output models is examined in some detail because despite the elegance and simplicity of input output analysis, there are considerable difficulties attached to its use for modelling technological change. The model developed for this project and described in Chapter 4 achieves considerable success in avoiding these difficulties.

3.1 A TECHNOLOGICAL CHANGE MODEL

The United Kingdom can be seen as a system, through which commodities flow between producers and consumers and in which commodities are made available or consumed by the operation of technologies. The minimum requirement for an energy model is that energy or fuels are one or more of the commodity flows documented in the model. Within the many possibilities that this specification allows, are models which explore the implications of a change in one or more of these technologies so that the magnitude or type of commodity inputs and outputs are changed. A technological change model, in the sense in which the term is used in this project is a 'before and after' type of model. The technologies and commodity flows before the change occurs is known and constitutes the 'before' picture of the system. The 'after' scenario is the one that pertains after the technological change, given that a number of specified circumstances remain the same. For example, such a model might investigate a typical technological change; say, the introduction of electric cars. This comparison might be made by determining the total requirements for electricity, coal, steel, motor spirit etc. before the introduction of electric cars and then after their introduction, given that passenger transport behaviour and demand remains otherwise the same and the technologies for the production of all other commodities in the system remain the same. In this example the 'before' case can be modelled and quantified using real data since the 'before' case can be represented by some approximation to 'now'.

Within the context of the definition of technological change models, a technological change might be either the introduction of a new technology (as in the example above) or the disappearance of an old technology or the partial substitution of one by another where either or both are pre-existing technologies, present in the 'before' scenario. Technological change is also represented in models, particularly 'dynamic' models which have a time dimension, as the gradual improvement in the technical coefficients of a technology; that is a gradual reduction in the ratio of inputs to outputs as the technology is presumed to improve its efficiency with the passage of time. This is a feature of many of the dynamic input output models such as EXPLOR-UK (3.1). This reflects both an improvement in efficiency due to accumulated experience in operating the technology and the gradual introduction of new technology which is disguised by the aggregation of a number of similar or related technologies. The former type of technological change model is of more relevance to this thesis. The model described is of the non-dynamic 'before and after' type.

Technological change may take place in the intermediate and primary sectors, or it may occur in the consumption sectors. An example of the former might be the introduction of a novel electricity generating technology. Here the product is already bought, by both intermediate demand and by final demand sectors, although the input requirement will be different to previous technologies, either in type or in quantity. Alternatively technological change might take place in a final demand sector, influencing the quality and/or quantity of consumer requirements. The introduction of loft and cavity insulation is an example of technological change is distinguished from the former in that there is no 'product' of the technology. The importance of this distinction will become clear in the following chapter where the project model is described. Technological change of this type may be dealt with by specifying demand in terms of 'useful effect' so that although distinction between the types of technological change is important for the <u>formulation</u> of the model, in practice there are considerable advantages in blurring the distinction through the concept of 'useful demand', also described in the next chapter.

3.1.1 Multisectoral models

It will be clear from the above and from the problem specification in section 2.5 that the model required will include specifications for technologies (CHP plant, heat only boilers, heat storage, power stations etc) and for commodities (fuels, electricity, low grade heat and others). This immediately suggests a two dimensional array although this is not the only approach, as demonstrated by Barrett (3.2 and below).

An additional feature of this type of 'technologies and commodities' model is the presence of feedback loops, in which the output from one technology is the input to another technology which produces the input to the first technology. An example of this is illustrated in figure 3.1. Coal is produced by coal mines and part of the production goes into coal fired power stations which produce electricity. Part of the electricity production (albeit a small part) is required by coal mines for the coal production process. This means that if an additional quantity of coal is required elsewhere in the economy, then the coal mines will have to increase their activity so as to provide not only the actual quantity of coal required (the first order effect) but also sufficient quantity of coal to provide for the additional electricity production to meet the additional requirements of the coal mines (the indirect effects.) Additional electricity will be required to produce additional quantities of other goods which are inputs to the coal mining process. For a system in which there are N commodities, it is possible to calculate N^2 numbers m_{ij} which represent the additional quantity of commodity i required to produce one additional unit of commodity j. The concept of intensities is discussed elsewhere (see 3.22 and section 4.3 below).

Although this feedback effect has been shown not to be very significant in the case of direct inputs and outputs investigated in this study (see Appendix 5), the inputs to the production of the capital equipment for CHP/dh (see figure 3.2) require further study and these effects are thought to be more significant, particularly if the period of build-up of CHP/dh capacity is investigated (see section 9.3.1.3 below).

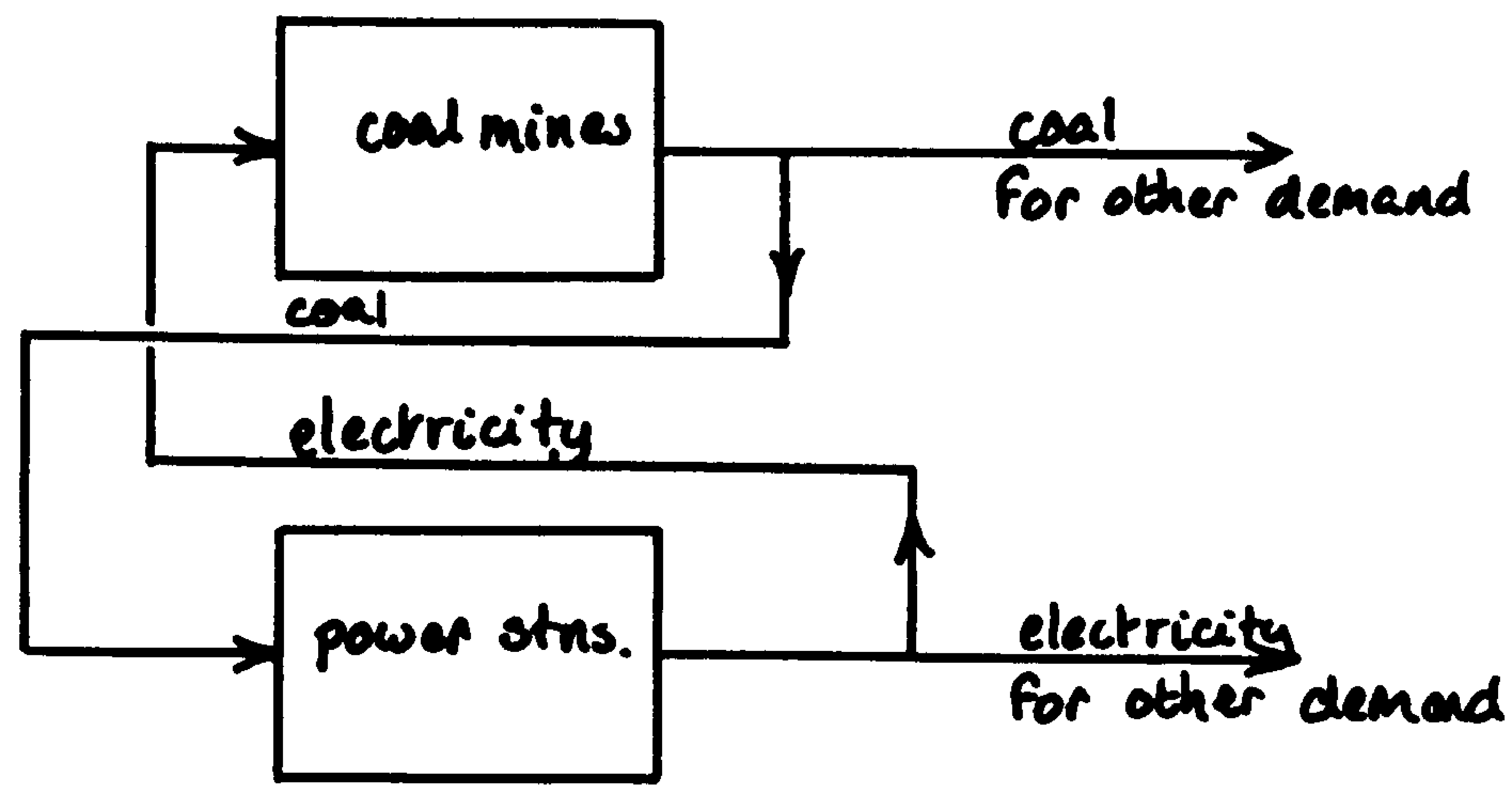

Figure 3.1

Feedback between production processes: the example of coal and electricity

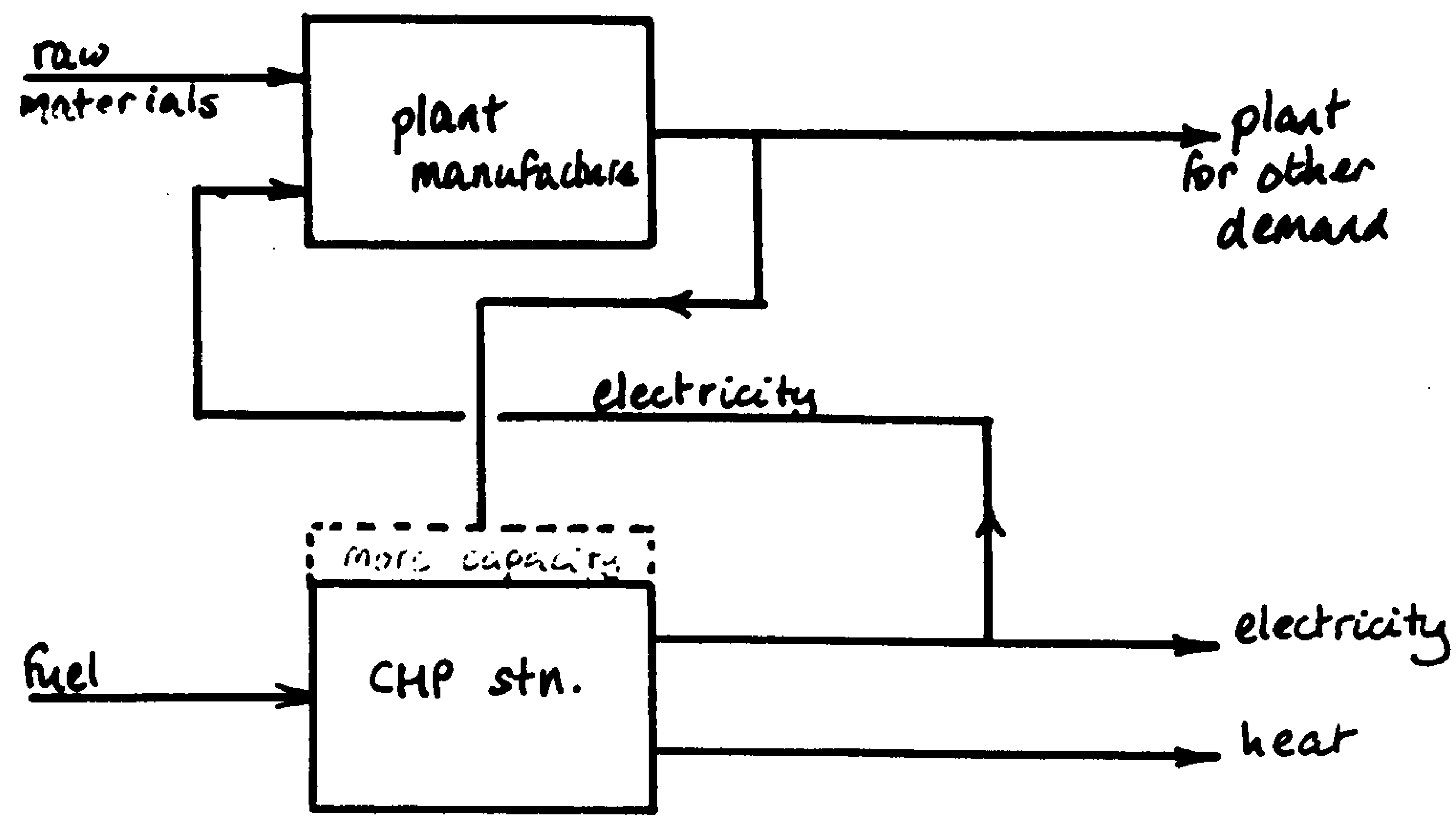

Figure 3.2 Capital construction in interacting system

A suitable model for this type of investigation must be sufficiently disaggregated so that important feedback loops can be identified. In practice, it is difficult to identify these in advance so that a more realistic approach is to disaggregate to a level of detail commensurate with the level of detail required in the output. However, it is strongly felt by the author that if the implications of the technology are to be investigated, then the model should be no larger, no more complex and no more general than is strictly required to address the questions outlined in Chapter 2. Thus the model developed for this project, though it refers to the UK and to use of fuels within the UK, is very different in concept from other UK energy models, such as SARUM (3.3), DYPHEMO (3.2) and EXPLOR-UK (3.1), in that there is not the same level of generality. The scenario to be tested contains only one technological change, ie the introduction of CHP/dh, and data collection and use is geared to that technology. This is in contrast to many other UK energy models in which policy, manifested by a whole range of technology, resource availability and demand changes interact. The intention for the model described here is that the effects directly attributable to the introduction of CHP/dh can be determined alone and in isolation from additional technological change which may occur contemporaneously with the introduction of CHP/dh. This is a vital distinction in that it separates this type of technological change model from the energy policy models which generate scenarios for future years based on a number of assumptions about policy, economics, demand, prices and available technologies. In those models the assumptions are built in and therefore not at the forefront of the mind when formulating policy. In this model they are not an unfortunate necessity covering absence of information - rather a central part of scenario formulation.

It is important to recognise that distinguishing the effects of introducing CHP/dh into an otherwise unchanged picture of the UK is a problem prior to that addressed by the policy model. The level of detail with which a policy model is capable of treating CHP/dh, or any other technology is limited if the model is not to require and generate incomprehensibly large quantities of data. However, it is also important to recognise that the introduction of CHP/dh in the UK will not, if it ever does, happen in isolation from other technological change. If district heating were seen as part of a programme of urban renewal, then it is likely that demand levels will also change as a consequence of reduced heating cost (perhaps) and better thermal characteristics of housing. For this reason any model attempting to achieve the objectives set out in Chapter 2 should be capable of being used or extended to examine these additional technological changes since the effects of these parallel changes are unlikely to be additive.

3.1.2 Problems with large scale models

Before reviewing some of these models which have features in common with the author's model, it is appropriate to indicate some of the problems of other models used in energy policy and other fields.

There are two main benefits to be derived from building models. One is an intended benefit. The second, though unintentional, may in fact be more important.

Firstly, the expected benefit and normally the explicit purpose, of building a model is the acquisition of model output which can be interpreted as the answer to a question or problem. For a number of reasons explored below, this benefit may not be fully realised.

Secondly, the construction process itself may yield considerable understanding of the system which is being modelled. This valuable insight may be lost to the model user, unless the model builder takes deliberate steps to make it available. Both benefits may be prejudiced by the use of inappropriate models or by using models for inappropriate purposes.

The intended benefits of using a model will be realised if the model output can be interpreted as an answer to the problem posed. The quality of the answer is a test of the success of the model. A successful model will produce answers which can be classified as 'acceptable, useful, or illuminating' but as pointed out by Labys (3.5), there is no absolute measure of 'validity'. Since the model is itself an approximation to reality, the output produced by a model cannot be expected to be an absolute representation of reality.

The reasons why the author has adopted a 'minimalist' approach to the construction of a model are related both to the need to produce adequate solutions to the problem and to the desire to construct a model in such a way that the enhanced understanding achieved by its construction is explicit .

Models may fail to achieve either benefit for two reasons which may be identified and thus, perhaps, avoided.

A model which is sufficiently general to address a wide range of questions may lead to a number of problems. The representation of a number of important features relating to CHP/dh, such as the time variation of heat and electricity demand, requires very large quantities of data. The data acquisition and handling for the construction of a still more general model would thus be unacceptably large if generality were to extend to, say, heat pumps. Consequently the usual approach is to use more aggregation than in the author's model in order to achieve this generality, but this leads to the further problem that the quality of output may be too coarse and insufficiently detailed to be of use. The author has thus avoided generality in the CHP/dh model.

With increasing size and comprehensiveness comes the problem of increasing complexity. Complexity carries a number of penalties. There are procedural ones associated with the tracking down and correction of incorrect or misleading parameters and relationships but more importantly, underlying relationships between variables become increasingly obscure and the model user is prevented from achieving any insight into the nature of the issues he is addressing. Complexity and size can also lead, particularly where iterative procedures are used, to the propagation of numerical error.

The obscurity perceived by the model user thus militates against the model user sharing the model builder's insights.

Since the model user can never share the experience of model building, the approach adopted in this project is to keep the model as transparent as possible. In other words all the parameters and the relationships between them are easily accessible to the model user and furthermore are sufficiently simple that the model user can identify clearly the relationships giving rise to the model output. Many models have been found to lack credibility because this is not possible.

3.1.3 Project modelling objectives

The observations recorded above had led to the formulation of a number of <u>modelling</u> aims which in turn have determined the type of model which was used to investigate the implication of CHP/dh use. These modelling aims can be stated as

The construction of a model

(a) which is sufficiently comprehensive to illuminate the problem area but which is no more detailed than is necessary so that the problems of size and over-generality can be avoided.

(b) in which the data generated can be readily identified as arising from particular causes or relationships

(c) which contains as few hidden assumptions and relationships as possible

(d) which can be described in English rather than Computer.

In other words, although the model used in this project cannot in itself be used to study technological changes other than those related to CHP/dh use, it does seek to be simple enough in structure so that it can be reproduced, with other data sets, to meet the requirements of other technical change investigations.

It is interesting to note that complexity in models often arises as a result of a desire to be accurate, indeed it is not unusual to see 'complexity' and 'accuracy' used synonymously (see Labys (3.5)). Increasing the complexity of a model may be a response to inappropriate model output. This response arises as a consequence of the view that the world is a complicated place. This may well be the case but it is the author's view that the use of models as a substitute for thought is likely to be self-defeating in designing policy and that a simple model used as an aid to thought may offer the best return in terms of effort invested. A simple model may be just as wrong, but it does allow the investigation and discussion of the data and the relationships between them.

Before describing input-output analysis techniques and the development from them which is used in this project, it is appropriate to review some other models which approach the impacts of technological change.

3.2 TECHNOLOGICAL CHANGE AND ENERGY MODELS

Interest in technological change models is comparatively small compared with the interest in policy models. However those selected below are thought to be a representative sample.

3.2.1 The Barrett DYPHEMO model

The DYPHEMO model is an attempt to build a realistic, dynamic energy flow model of the UK. In this attempt it largely succeeds, being a policy tool capable of determining total energy flows for a given period of time by calculating for hourly intervals the characteristic demands for a large number of sectors in useful energy terms and, by determining the contribution to supply based on a number of input specifications of technologies available, conversion and distribution efficiencies and capacity limits. The model is primarily directed at examining the temporal characteristics of supply and demand for novel technologies, particularly those which are renewable and at determining the effects of 'improvements' in the UK energy system brought about by conservation, improved efficiencies, better end use matching and by behavioural changes (such as better use of heating systems and car-sharing). As in this project, no attempt is made to examine the pressures that might lead to these changes.

By allocating supply to calculated demand DYPHEMO operates as a 'motorised Sankey diagram' (Barrett's phrase) of considerable complexity, having an allocation algorithm capable of modification to include both conventional and novel technologies.

However, it seems that while DYPHEMO provides a way of sketching out an enormous range of possible one year scenarios, it falls into some of the difficulties described in the previous section. Firstly, by being so comprehensive in its coverage, DYPHEMO produces insufficient detail for the requirements of policy-makers to which it is addressed. This is not in itself a fault but DYPHEMO could only be used as a sketch, to which further detail should be added. This is because technologies are introduced one by one and while DYPHEMO gives a very good picture of the system with a large number of technologies acting together, it is insufficiently detailed to provide, for example, analyses of the temporal interactions of different CHP/dh technologies.

While formal elegance is not necessarily desirable in itself, it does make a model easier to understand, sensitivities easier to analyse and interdependence between externally valued variables easier to spot. Barret admits (p.34) that DYPHEMO may be difficult to understand but he encountered no serious difficulties with respect to the above items. However, it is difficult to see how, for example, changes in the structure of industry's production, particularly with respect to the production of energy plant itself, could be included in the model as presently structured. Neither can feedback-loops be catered for in DYPHEMO. Although these are of negligible importance in the case of existing technologies, it would be difficult to incorporate those that appear in novel technologies without resort to iterative procedures, with the consequent computational difficulties inherent in that approach.

Although insufficiently detailed for the present study DYPHEMO remains a very successful model for scenario generation with a very broad range of novel and existing technologies and shares a number of the basic ideas with the model described in this thesis.

3.2.2 The SARU Energy Demand Projections model

The SARU model is one of the two principal UK energy models based on an input output approach. (The other is the EXPLOR UK model, developed by the Department of Applied Economics at Cambridge University).

The general characteristics of input output models are described elsewhere (3.7, 3.8, 3.9 and section 3.3 below).

The purpose of the model is to generate energy demand scenarios based upon 'business as usual' types of assumptions. This is done by the use of a causal model relating fuel choice, production, distribution, pricing and consumption of energy. The Energy Demand Projections (EDP) model stimulates the national energy economy, running forward from a preset date for a number of years into the future - each variable describing the base year is defined for future years by the use of exogenously defined time series. The variables used are predominantly 'economic', reflecting the interest of the SARU team in the factors which determine the decisions of business and industry. Like the model described in this thesis, the EDP model is demand driven. The demands of consumers and government are calculated from GDP data, together with the requirements for capital equipment (calculated from capital-energy production functions) and exports. These requirements drive a 24 sector input output matrix describing industrial demand. Total energy requirements are generated by use of the Leontief inverse of the matrix (see section 3.3.1 below), total energy requirements for each year are calculated. The coefficient for the input output matrix are themselves subject to change from year to year to reflect improved technology and energy-capital substitutions and a new inverse is calculated for each year through which the projection runs.

This model is particularly interesting since the procedure and structure by which energy requirements are calculated is very similar to the model described in this thesis. This structural similarity exists despite the fact that the SARU/EDP model is concerned primarily with economic matters such as relationships between consumer disposal income, GDP, fuel prices and trade balance and their effects upon energy demand.

The purpose of the SARU/EDP model is also different from that of this model, being primarily to project total energy demand as a policy making tool. However, the use of an input output matrix and its inverse to describe intermediate demands and driven by a final demand specification is very similar.

3.2.3 Electricity supply and demand models

An important feature of electricity production is the non-linear relationship between inputs and outputs. The quantity and type of inputs required to produce a quantity of electricity (measured in GWh) depends upon the rate at which they are required, in other words it depends upon the load (measured in GW) on the system. When the load is low, the plant used to supply it are dominated by large and efficient plant and by nuclear plant. As the load increases, the average efficiency will fall, the proportional contribution (although not the absolute contribution) of nuclear power will be reduced as large numbers of small and less efficient plant is brought on stream. Thus it is difficult to model electricity production using simple linear models. Barrett (3.2) overcame this problem by stratifying power stations into a merit order based on fuel input type (nuclear power at the top, followed by coal, oil and gas/diesel for existing plant). Efficiencies are then assigned on the basis of load factor (high load factor, high efficiency). However, this is not a very accurate reflection of the UK electricity supply system where merit ordering is based on a marginal cost (3.10), a function of efficiency and fuel price which leads to a more diffused ordering of fuel-input types.

3.2.3.1 The Lencz model

This model describes the electricity and heat supply systems of Czechoslovakia (3.11, 3.12). The specific purpose of the model is medium term forecasting to aid system planning. It is an interesting model on a number of counts. Firstly it incorporates specifically relationships between electricity producing plant and CHP plant and secondly it recognises explicitly that electric power systems operate in two time domains. The hour by hour variations in demand determine the quantity of electricity required and the required capacity of the system. Changes in the capacity of the system however take many years to effect and a model designed as a planning tool must take account of both these effects. The Lencz model draws an extensive data bases describing the power plant, its availability, reliability, fuel requirements and economic and ecological parameters. By calculating first the quantity of heat required from CHP plant, the quantity of electricity available from this source is then determined. The operating regimes of conventional power stations are then determined using the data bases listed above. Economic characteristics are then calculated. The overall system is optimised using linear programming techniques.

3.2.3.2 The Verbruggen model

The model described by Verbruggen (3.13) is designed to determine the economic performance of CHP steam plant in a district heating 'park' where a number of CHP technologies act together to provide heat. The model operates on the principles described by Turvey and Anderson (3.14) for electricity. The estimated heat load duration curve for Belgium is described by a set of three equations (describing high, medium and low demand load factors) and scaled to a peak load of 100 MW. The running costs and capital costs for the available CHP/dh technologies are used to determine a merit order, break even load factors and required capacity of each type of heat producing plant. It is assumed throughout that electricity produced in conjunction with heat can be 'dumped' to the electricity system. Electricity revenues are calculated and used to off-set the cost of fuel and the total cash flow is determined.

While the results of this type of study are very useful in determining the requirements of an individual group of CHP/dh plant, the most fragile assumption made in this type of model is that electricity can be sold to the electricity supply system without appreciable effect upon the electricity supply system. The implication of this assumption is that the electricity supply system is sufficiently large that electricity supplied by the CHP plant is insignificant. The assumption would break down if the electricity capacity of CHP plant were significant, as it would be if there were a number of CHP 'parks'.

3.2.3.3 The CEGB models

The Electricity Supply Industry devotes considerable effort to the determination of future plans and assessment of the technological options available. This activity is separate from the operational planning activity, carried out on a daily basis to minimise the cost of electricity production by appropriate use of the plant available at any given time.

The aim of the Electricity Supply Industry's long range planning is the determination of appropriate investment strategies for the industry in order that it meet projected future demand in a cost effective manner. The planning process thus involves the determination of projected demand and the formulation of an appropriate generation investment strategy to meet that demand.

The principal tools used by the CEGB for medium and long range planning are the SIMOP and MIXLP models described in a submission by the CEGB to the Sizewell 'B' Public Inquiry (3.15). The SIMOP model simulates the period up to the year 2000 and the MIXLP model simulates the period beyond that date.

SIMOP is used to simulate the lifetime operation of a plant and calculate its net effective cost. Assumptions are made about the plant available for power generation, about the operating characteristics of the plant, the fuel burned and the cost of that fuel. These are fed, as input, to the model which then combines them with a forecast of demand to produce the net effective cost of the plant. This can then be compared with alternatives. Demand is represented in the model by load duration curves for each of 8 time periods. These 8 time periods represent characteristic weekday and weekend periods during each of 4 seasons. System loading is simulated by a linear programming procedure which allocates the minimum cost set of power plant to meet the demand. The load durations are derived by examination of the load duration curves for corresponding time periods in previous years. Account is taken of the demand characteristics of a number of demand sectors together with a number of economic indicators, grouped into scenarios.

The MIXLP model is a very much simpler model which works with time periods of one year, rather than the eight time periods used by SIMOP. The MIXLP model can optimise the plant mix over a period of a number of years.

The SIMOP and MIXLP models are integral with the Electricity Supply Industry's overall forecasting and planning activity and should be viewed in that light. As is the case with many models, most of the interesting activities are external to the model. This is particularly the case for the demand generation procedure.

There is no direct feedback between the electricity prices generated by the model and those which generate the electricity demand. Electricity demand is generated from economic indicators, electricity prices and projected activities of the consuming sectors. However, the outputs of the model includes factors which will indicate these. While this problem is not peculiar to the SIMOP model, this problem does highlight a significant problem with forecasting models of this type.

3.3 INPUT OUTPUT MODELS

Having reviewed some energy models relevant to this study, it is now appropriate to examine a large class of models which are capable of representing the flow of commodities (including energy) through industrial processes (including energy conversions) to consumers. This type of model is extensively reviewed because input output analysis offers substantial advantages for investigating the 'knock-on' effects of technological change. However, as will be shown, the economics heritage of input output analysis means that it is in many ways unsuitable for the assessment of the technological impacts of technological change. It is important to understand these problems in order to appreciate the importance of the novel approach taken by the author to the modelling of the CHP problem and solving these difficulties from the original framework of input output analysis.

3.3.1 The coefficient matrix and the Leontief inverse

Input output models are based upon input output tables. These are accounting frameworks which reveal the inter-relations between industries in an economy. The formulation of these tables and their subsequent use as the basis of models of inter-industry transactions is due to Wassily Leontief. His purpose in developing input-output techniques was to give empirical substance to his general theory of production which is based on the idea of economic interdependence (3.16).

The central principle of input output analysis is that of the total quantities of commodities produced by an industrial economy, some will be sold to final demand (consumer) sectors and the remainder will be used in the production of other items in the total commodities list. In other words, every sale of commodity i is also a purchase of commodity i, either by final demand or by industry in order to produce some other commodity.

This basic model of an industrial economy can be represented in matrix notation, as

$$q = Xq + f \tag{3.1}$$

where q is the vector of total production whose elements

q_i are the quantity of commodity i produced in one year

f is the vector of final demand whose elements

f_i are the quantity of commodity i purchased by final demand

and X is the square matrix of intermediate demand whose elements

x_{ij} are the quantity of commodity i which must be purchased as input to the production of one unit of commodity j.

This is illustrated in figure 3.3.

Equation 3.1 may be rearranged to give a transformation matrix between final demand and total production, as follows

$$q = (I - X)^{-1} f \tag{3.2}$$

where I is the identity matrix.

Provided that the technical coefficients of the matrix X can be assumed to be stable and independent of demand or total production levels, then for any given final demand, the total quantity of production required to meet it can be calculated. In other words the Leontief inverse $(I - X)^{-1}$ can be interpreted as a matrix of intensities where the element in the i'th row of the j'th column is the total increment in the production of i required to provide one unit of j for final demand.

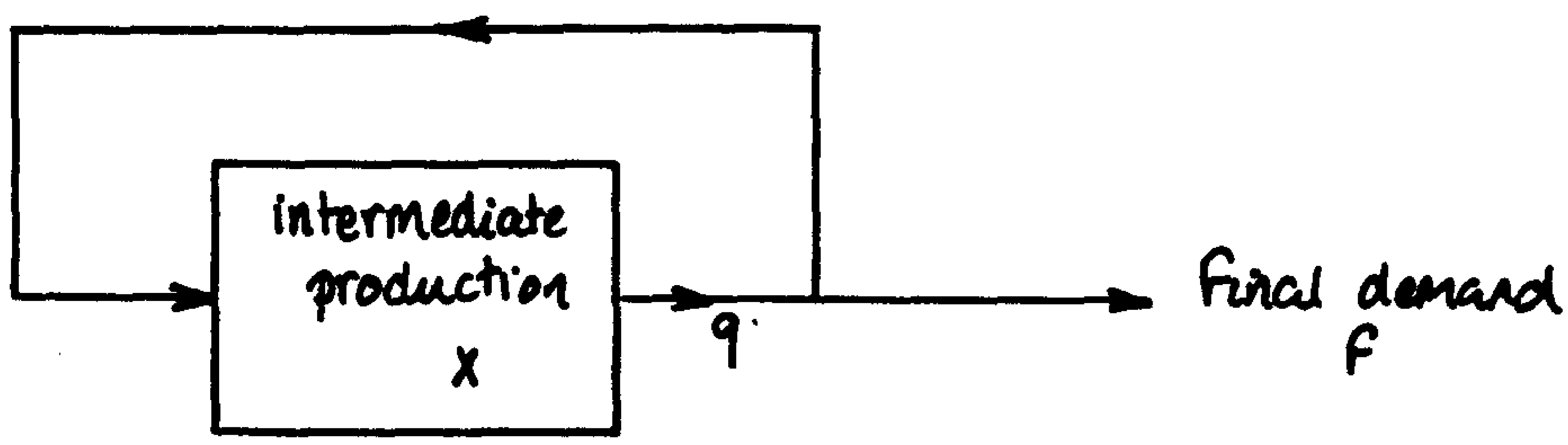

Figure 3.3 Leontief model of economy

That this is indeed the case can be seen from noting that $(I - X)^{-1}$ can be expanded as a converging series, since $-1 \leqslant x_{ij} \leqslant 1$ and $\Sigma_i x_{ij} \leqslant 1$. Thus $q = (I - X)^{-1} f = f + Xf + X^2f + X^3f + \ldots\ldots$ 3.3
where the final term $X^{\infty}f$ is a zero vector since X^{∞} will be a null matrix.

Equation 3.3 shows quite clearly that in order to provide final demand, the total quantity of commodities required will be firstly the final demand itself (f), plus the direct inputs required to produce that final demand (Xf), plus the inputs required to produce those inputs (X^2f) and so on. This may be seen as a process analogous to that of energy analysis, with the exception that whereas energy analysis truncates the series at the third or fourth iteration, the Leontief inverse extends the series to infinity. The Leontief inverse may be used for additional purposes such as determining the impact on the price of all commodities of a change in the price of one or more commodity.

3.3.2 Derivation of the technical coefficient matrix

The matrix of technical coefficients X is a derived matrix and must be calculated from primary data.

The primary data from which the technical coefficients are calculated is collected in three matrices recording the production, purchases from domestic production and purchases from imports by each industry. The make matrix A has elements a_{ij} which are the quantity of commodity i produced by industry j in the data year. The domestic absorption matrix B has elements b_{ij} which are the quantity of domestically produced i purchased by industry j and similarly c_{ij}, in the matrix C of imports absorption, is the quantity of i purchased by industry j from foreign sources. Matrix C is not normally used directly in the calculation of X (see section 3.3.3.3 below). Matrices A, B and C are normally square since industry i is defined as being the group of industrial establishments whose principal product is commodity i. The nomenclature of commodities and industries is thus the same in these transaction tables, the largest elements in the make matrix being the principal products lying on the leading diagonal of the make matrix. Entries in the absorption matrices are much more scattered. The picture of the economy is completed by a final demand vector f in which the purchases of the non-intermediate sectors are recorded (ie householders, government departments, exports and fixed capital formation).

This method is recommended as the appropriate way for nations to present their input-output transaction tables by the United Nations (3.19). Countries which construct input output descriptions of their economies accordingly collect the necessary data with this end in view. In the United Kingdom, information about industrial activity is collected through the Census of Production (for example 3.18) in a form which will facilitate the construction of national input output tables. Input output tables were constructed for the United Kingdom from primary data for 1968 and updated for 1974 (3.17) with industries and commodities disaggregated to 90 sectors.

In order to determine the technical coefficient matrix, some assumption must be made about the way in which industries operate to produce commodities. The necessity of making these assumptions arises from the observation that many industries make non-principal products and therefore have more than one entry in the appropriate column of the make matrix. It is then important to ascertain how the inputs to the industry are distributed between the principal and non principal products. The question which determines how X is calculated can be posed as 'Are the inputs purchased by an industry the same for all the commodities it produces or are they specific to the commodities produced?' If the former than the inputs to the industry will not vary in composition when the product mix changes and the 'industry technology' assumption procedure is used. The industry technology assumption is appropriate where non-primary products are produced as an inevitable by-product of the primary product as for example the production of fuel gas as a by-product of coke production. If input structures are specific to the product mix then the 'commodity technology' assumption is appropriate if it can be further assumed that the inputs to the production of a particular commodity are the same in whichever industry produces it. This assumption might be appropriate where the production by an industry of a subsidiary product is as a result of a subsidiary activity.

In practice, it is normally inappropriate to apply either technology assumption to the whole economy since different industries behave differently in this respect and it is normal to adopt a hybrid approach, making the appropriate assumption about each industry.

Where commodity technology pertains, a product mix matrix P is calculated by dividing the elements of each column by the column total, ie

$$P = A\hat{g}^{-1} \qquad 3.4$$

where $\hat{g} = gI$

and g is the column vector of total industry outputs ie

$$g_j = {}_i\Sigma a_{ij} \qquad 3.5$$

An input mix matrix R is also calculated by dividing the elements of B by the total industry production

$$R = B\hat{g}^{-1} \qquad 3.6$$

Post-multiplying both sides of equation 3.6 by $\hat{g}$ and post multiplying by i, a unit vector then

$$R\hat{g} = B$$

and thus for the base year

$$Rg_0 = Bi$$

where the zero subscript denotes the data-base year by definition (see figure 3.4)

$$q_0 = Bi + fo \qquad 3.7$$

and hence

$$q_0 = Rg_0 + f_0 \qquad 3.8$$

For the data base year, equation 3.4 can be written as

$$Ai = Pg_0 \qquad 3.9$$

but since by definition

$$q_0 = Ai \qquad 3.10$$

then $q_0 = Pg_0$ 3.11

or

$$P^{-1} q_0 = g_0 \qquad 3.12$$

Substituting this in euqation 3.8 gives

$$q_0 = RP^{-1} q_0 + f_0 \qquad 3.13$$

Which is directly anologous to the original expression of the Leontief model when applied to the base year so that since

$$q_0 = Xq_0 + f_0$$

Then

$$X = RP^{-1} \qquad 3.14$$

This is the equations used for determining the technical coefficients matrix for commodity technology.

In order to determine the technical coefficients matrix for industry technology, the market share matrix D must be determined by dividing each industry's production of commodity i by the total production of commodity i

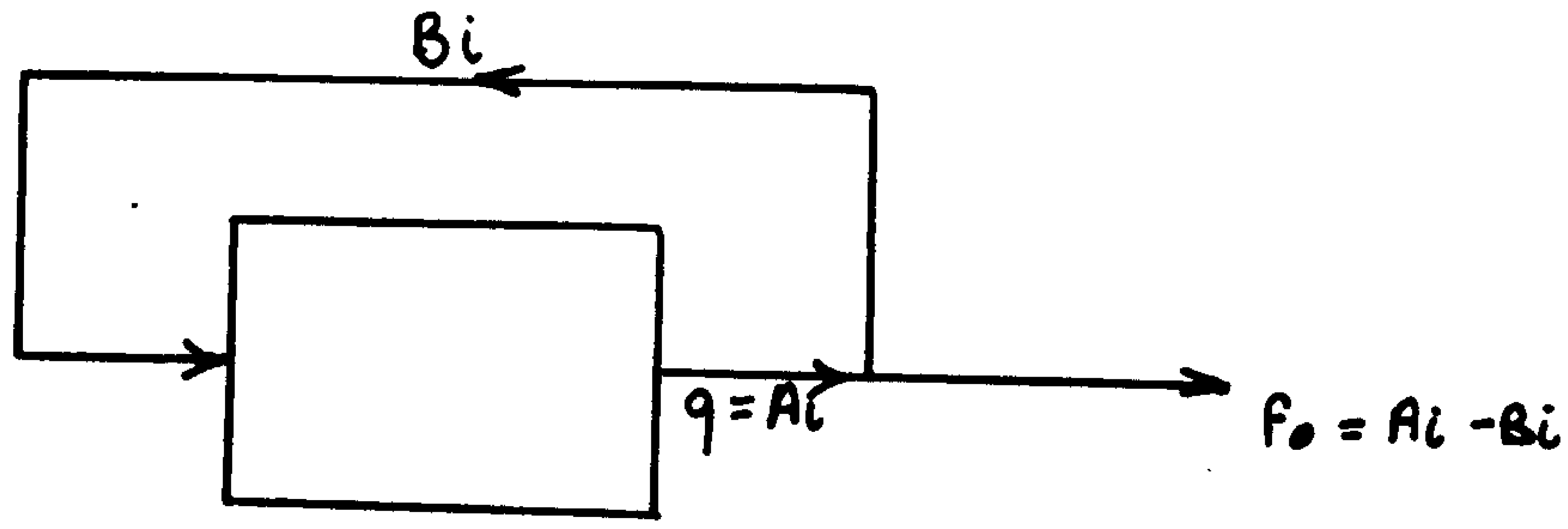

Figure 3.4

Input-output model of an economy for a database year (year zero)

$$d_{ji} = a_{ij}/q_i$$

or

$$D = A'\hat{q}_o^{-1} \qquad 3.1$$

so that

$$A'i = Dq_o$$

but $A'i = g_o$

so that

$$g_o = Dq_o \qquad 3.16$$

Substituting into equation 3.8 gives

$$q_o = RDq_o + f_o \qquad 3.17$$

and, again by comparison with the model equation

$$X = RD \qquad 3.18$$

A numerical example of these calculations is shown in Appendix 3 for a two sector economy.

Once calculated, it is assumed that the elements of the technical coefficients matrix are independent of total production levels, in other words, that they reflect the technologies of production by describing a linear relationship between the inputs and outputs of each technology. Thus from the base year the model can be generalised to allow the calculation of the total commodity requirements for any specified final demand. Technical coefficients may be made to change to reflect some technological improvement or change,either explicitly or by following a predetermined time function. This latter is the so called dynamic input output model.

3.3.3 Spurious changes in coefficients

Several problems arise from using this type of formulation to investigate technological change. The necessity for making either or both of the commodity technology or industry technology assumptions and the problems arising from the use of the industry technology assumption have been remarked above and by the author and colleagues elsewhere (3.20). However, there are other factors apart from the level of demand which may affect the coefficients of the Leontief inverse apart from technological change and considerable study of these has been made over the years, eg Riefler and Tiebour (3.34). The approach developed by the author and colleagues is designed to obviate these difficulties which are outlined below. They arise from the use of financial units of accounting for commodity flows and industry output, the level of aggregation of the data and the treatment of imports.

3.3.3.1 Financial units

In order to derive the Leontief inverse, it is necessary that all the coefficients of the make and absorption matrix be expressed in common units. This requirement arises from the necessity that the column totals be summed to determine the product mix matrix (see Appendix 3). Because of this requirement, but primarily because of the primary interest of economists in the use of input output analysis, it is usual to express the make and absorption matrices in financial terms; the value of production either at point of sale prices or more usually at ex-works prices. A consequence of this is that input output coefficients may change for reasons totally unconnected with technological change. For example, relative price levels may change through time, making it difficult to project future coefficients unless constant prices are used throughout the model. This will necessitate the collection of constant price information if input-output coefficients for one particular year are used to gain information about subsequent years. While this is not a serious theoretical problem, it further extends the data collection and organisation problem which may already be severe. More difficult to deal with is the problem of preferential pricing which means that the value of goods exchanged between industries may not be proportional to the absolute quantities transferred. Preferential pricing may arise for a number of reasons; forward ordering, assured demand, economics of large sales etc. Changes in these conditions would lead to a change in input output coefficients without any technical change having taken place.

3.3.3.2 Aggregation

The basis for disaggregation used by the CSO (3.17) and many others in the UK is the Standard Industrial Classification 1968. This classifies industries by grouping establishments according to their principal product. However, industries taken as a whole do not necessarily have constant product mixes and hence the input mixes too will vary as non-principal products assume a greater or lesser importance. As shown in section 4.2 it is more appropriate in examining technological change to use industrial processes rather than industries, as a basis for disaggregation in the areas of interest. In practice, since non-principal products are often related to the principal product of an industry, the appearance of a non-principal product in the matrices will depend upon the level of aggregation of the tables. The more aggregated the table, the more likely it is that the non-principal products of an industry will be aggregated with the principal product.

3.3.3.3 Imports

While the approach to the development of Leontief inverses, of various sorts, under a variety of assumptions, is fairly standard for a wide range of models, the treatment of imports is less uniform and a number of approaches are possible.

A number of models, in general the simpler and smaller ones, confine their attention only to domestic flows. This approach is also appropriate for economies where the volume of international trade is small compared with the volume of internal flows.

An alternative approach to this is that originally described by Leontief (3.2.4) treats imports explicitly by adopting a second and additional absorption matrix C in which the elements c_{ij} describe the quantity of commodity i imported by industry j. An additional final demand vector is also required which describes the purchases of imported goods by the final demand sectors. The vector of imports is thus a function of the final demand for domestically produced goods (which require imports for their production) and the final demand for imported goods. This is illustrated in figure 3.5.

If the subscript D is used to describe domestic production and the subscript I to denote -mports, then equation (3.8) may be rewritten as

$$q = X_D\, q + f \qquad 3.19$$

The table of absorption from imports, analogous to B, denoted C can be used to calculate a commodity x commodity imports matrix : for the commodity technology assumption

$$X_I = C\hat{g}_o^{-1}P^{-1} \qquad 3.20$$

A vector of commodity imports y can be defined together with a matrix Q where elements q_{ij} describe the quantity of input i absorbed directly to produce j, so that

$$y_o = Qi + f_I \qquad 3.21$$

If it is assumed that imports are functions of the total quantity of goods produced then

$$Q = X_I\hat{q}_o$$

and therefore

$$y_o = X_I\hat{q}_o + f_{oI}$$

Total requirements for inputs to domestic production are thus

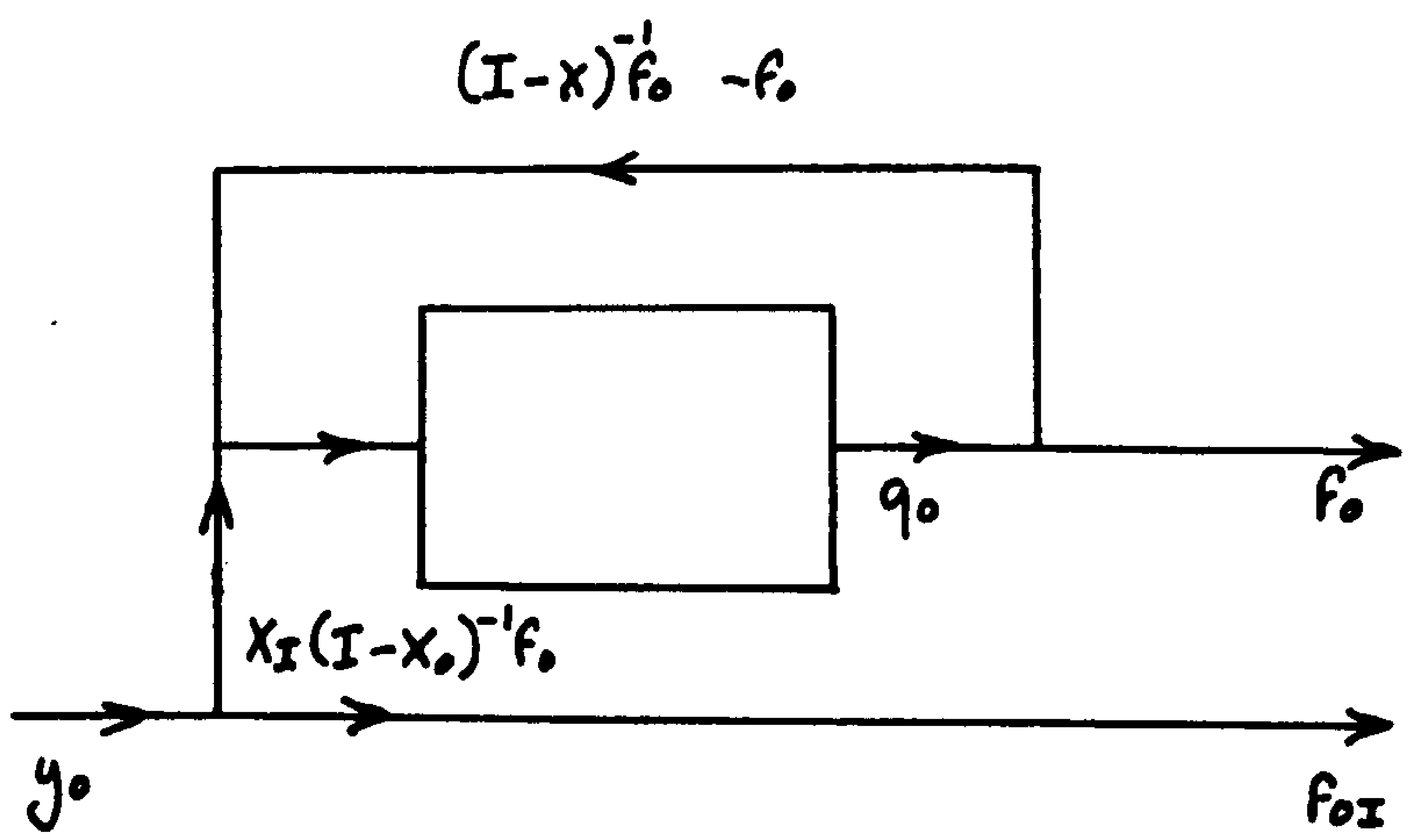

Figure 3.5 Leontief treatment of imports

$$(X_I + X_D)q \quad 3.22$$

and since $q = (I - X_D)^{-1}f$, then

$$y_o = X_I\ (I - X_D)^{-1} f_o + f_{oI} \quad 3.23$$

or for any other year

$$y = X_I(I - X_D)^{-1} f + f_I \quad 3.24$$

This equation shows that the vector of imports depends upon final demand from domestic production and final demand from imports. The vector of import requirements for domestic production is given by the transformation matrix $X_I(I - X_D)^{-1}$.

While this approach offers considerable mathematical elegance, it requires that important assumptions are made whose validity under certain circumstances would be in grave doubt. In particular it is assumed that for input to any particular process, imports and domestically produced goods are required in fixed ratio. While this assumption would have some validity if the imported inputs were unavailable from domestic production, it is clear that a substantial part of the imported bill of goods is in direct competition with domestically produced goods. In this case the decision to use imported inputs will depend on issues such as delivery times, quality and price. Price is likely to be the principal of these but it is not independent of the level of final demand. This is because final demand includes the demand for exports. The demand for exports, normally determined exogenously will have an effect upon the value of the pound which will in turn determine the relative competitiveness of imports compared with domestically produced goods. Thus the coefficient matrix the commodity x commodity matrix for imported goods is subject to wide variation for reasons totally unconnected with technological change.

A simplified version of this approach described by Chiou-shuang Yan (3.23) is the use of a vector of imports which is subtracted from final demand. In other words imports are treated as a negative final demand. While this has the advantage of computational simplicity, the technical coefficients calculated on this basis will give a misleading impression of the input requirements of technologies which use imported goods. A slightly more sophisticated version of this approach is to split imports into those which compete with domestically produced commodities and those which could not be produced domestically. Those which compete are added directly to the inputs to domestic production and those which do not are shown in the make matrix as an additional column representing the process of 'importing'. This form of representation implies a constant mix of non-substituting imports and is, of course, a nonsense, as pointed out by Lecomber (3.25) but it does offer the advantage that the coefficients of the Leontief inverse reflect the producing technologies more accurately, although even this is at the cost of considering foreign firms as if they were identical with domestic firms.

In practice, although there are internationally agreed standards about the treatment of imports in input output analysis, the precise way with which they are dealt will depend upon the purpose of the model. The treatment of imports in a range of input output models of a number of countries is compared in the annexe to Lecomber's paper (3.25). Broadly speaking, if technical coefficients are the primary interest of the modeller then imports will be treated as if they were domestically produced. If prices, foreign trade and GDP are the main interests then alternative treatments are adopted. The Cambridge Growth Model is an example of this type of treatment, described by Barker and Lecomber (3.26). Here GDP sets a limit on final demand (excluding exports), total demand is then determined via an input output model. Domestic prices, foreign prices and an exchange rate are specified exogenously and the split of total commodity requirements between domestic production and imports is then calculated for each commodity based on whether or not imports are substitutable and upon relative price. When this has been determined, an export specification is derived which will provide the necessary balance of payments. This new specification of final demand leads to the next iteration. Convergence is rapid since exports are a relatively small part of final demand.

Models which are designed to determine the implications of technical change on total demand, do not in general need an endogenous constraint upon balance of trade and either no attempt is made to achieve a balance, or some ad hoc approach is used. Input output models are capable of extension to programming models for the treatment of foreign trade, as for example the ESRI model of Ireland described by Simpson (3.27) or the model of New Zealand described by Blyth and Crothall (3.28). A criticism of programming models of this type frequently (and validly) made is that neither governments nor anyone else is in a position to optimise anything at a national level in any but the most rigidly planned economies (and not even here if the volume of foreign trade is of any size).

This discussion of the treatment of imports in conventional input output models shows that the problem is far from adequately resolved. The alternative treatment proposed and used by the author in the next chapter by-passes many of the problems described here.

3.3.4 Input output models

Since input output analysis is of interest primarily to economists, the range of models that have been produced and the types of problem which they address are in general outside the purview of this thesis. However, a brief review of the field will reveal that there are four principle areas of investigation viz, econometric studies of various sorts (for example the Cambridge Growth Model), impact models which investigate the implications of an economic policy decision on the economy as a whole and on its constituent parts (early and classic examples of this are Leontief's study of the impact upon the American economy of possible disarmament (3.29, 3.30) and of the implications of deliberate reduction of imports and exports to reduce US dependence upon foreign trade (3.31)), interregional studies (a major and typical example of this type is the model of the Shetlands economy and its interactions with the mainland (McNicoll, 3.32). A comprehensive review of interregional and small region input output studies in the British Isles is given by Morrison 3.33) and resource, intensity and technological change models. This last group, although diverse, are linked by the fact that their primary focus of interest is not the economy as a whole but on the particular role of one or more particular commodities or industries.

Resource models are directed at determining the quantity of a particular resource required by a nation or region in given circumstances. Energy is probably the resource most frequently studied. A very typical example is the model described by Se-Hark Park (3.35) which is constructed to show the total energy demand given levels of final demand and the state of technology.

Of more general interest are the models used to determine intensities of goods and services. If the Leontief inverse $(1 - X)^{-1}$ can be called M, then the element m_{ij} represents the total quantity of commodity i required to produce one further unit of commodity j; in other words m_{ij} is the 'i intensity of j'. The use of £m as the units of computation for the matrix of coefificients, hields results in the form of 'm_{ij} £m of commodity j'. The expressing of the energy data in the form of kWh/£m requires the subsequent division by an appropriate price for energy.

Wright (3.36) has computed the energy intensity of 91 commodity groups using data from the 1968 and 1963 input output tables (3.1). A serious deficiency in this approach is the assumption that energy prices are independent of the purchasing sector. In theory it would be possible to obtain information about prices for each sector, incorporating it as a multiplying matrix after calculation of the Leontief inverse, but in practice the data collection process would be time consuming. Energy intensities calculated in this way do not include energy inputs embodied in capital. This inclusion is normal where energy intensity is calculated iteratively 'by hand' (see Casper 3.22). Common and McPherson (3.37) have taken this one stage further and calculated the 'roundaboutness' of electricity inputs to commodity production. Roundaboutness is the ratio of direct inputs of electricity to indirect inputs of electricity.

The calculation of energy and other resource intensities by the Leontief inverse, suffers from some of the drawbacks of input output analysis in general. The difficulty with the non-uniformity of fuel prices has already been mentioned. In addition there is the problem that the use of the technical coefficients matrix implies a set of assumptions about the technology (industry or commodity?) and some treatment of imports. Conventional, 'by hand' calculation of energy intensities allows appropriate assumptions about the energy intensity of imports to be made. Input output calculation of energy intensities is less flexible, the usual approach being to impute to imported commodities the same energy intensities as domestic commodities, although production technology abroad may be totally different (for example, electricity may be derived principally from hydroelectric sources rather than from fossil fuels). The approach devised by the author and described in the next chapter makes explicit these assumptions and shows how energy intensity might vary with differing assumptions.

Technological change input output models are typified by that described by Ayres and Shapanka (3.38) and based on Clopper Almon's INFORUM input output model of the United States (3.39). In this model, which is dynamic, the coefficients of the input output matrix are allowed to change to reflect the substitution of one technology for another. The trajectory of the technological change, as represented by the technical coefficients is calculated for each commodity by fitting a logistic curve to historical data. The model is then allowed to run for future years, giving a forecast of total demand and inter-industry flows for those years. The capital equipment required to effect these substitutions is not explicitly modelled.

By contrast, in the technological change model described by Carter (3.40) technological change is regarded as embodied capital and a capital coefficient matrix is used to determine the capital input required to effect a particular technological change. Alternative production technologies are entered in the matrix in separate columns and the resulting rectangular matrix is solved by linear programming techniques.

3.3.5 Concluding remarks

Input-output models have an elegance not often found in other models. They can contain a wealth of detail while retaining a simplicity of form. There is considerable interest, not only in the use of input-output analysis for econometric purposes but also for the calculation of resource and energy intensities. However there are considerable difficulties with the use of conventional input output analysis due to aggregation, treatment of imports, appropriate linearity assumptions and allocation of secondary products. It is hoped that the approach outlined in the next chapter, while not solving these problems will demonstrate that it is possible to side-step many of the difficulties.

4. STRUCTURE OF THE CHP/dh ENERGY FLOW MODEL

This chapter describes the structure of the model developed by the author to determine the implications of a large CHP/dh programme. While the model has roots in the concepts of input output analysis, the model described shares very few characteristics with input output models with the notable exception that a matrix of intensities is used to determine total commodity requirements. However, most of the basic concepts of input output analysis have been changed or distorted beyond recognition, including the technical coefficients matrix, industries, commodities, technology assumptions and representation of technological change, imports and quantities of commodities. It will be shown that these conceptual shifts not only lead to a model which is more appropriate to the issue at hand but that the approach adopted, while not necessarily solving the problems of input output analysis, nonetheless circumvents many of them in this instance.

The author is indebted to colleagues at the Open University during the period 1975 to 1978, to whom much of the credit for developing the basis of the model, as represented by equation 4.3, together with the use of physical units must go(4.1). However, the model devised by the group during that period had an entirely different purpose and philosophical basis to the model described here.

The 1975 model was intended to be a very large, multipurpose model capable of giving answers to a very wide range of resource utilisation questions. Areas for which data was collected included energy, copper, aluminium, building materials and iron and steel. In retrospect, that model would certainly have fallen into the problems described in section 3.1.2 above. No resolution to the problem of treating imports was found; the approach adopted in this thesis project is entirely original.

The second most fundamental difference between the 1975 model and the present model, after that of size and comprehensiveness, is in the treatment of constraints. In the 1975 model, constraints on processes (see section 4.4.1 below) were seen as unfortunate necessities to get over the 'difficulty' of a non-square matrix. In the model described here, they are seen as expressions of technological choice.

The 1975 model was to be of the 'problem in, answer out' type. No attempt was to be made to enhance the understanding of the model user by making the model's relationships open and transparent. Thus the present model represents a major departure from that philosophy.

Work on the 1975 model was abandoned in 1978 due to lack of funds. The model developed for this project (no previous attempt to examine CHP/dh had been made) is based on an entirely new data base.

The model presented here should not in any way be interpreted as an attempt to challenge or reform conventional approaches to input output analysis. Input-output analysis provides some useful approaches to dealing with econometric problems. Some of these approaches are appropriate to a model of technological interactions and have therefore been stolen from econometric science and modified for alternative purposes.

4.1 PHYSICAL UNITS

While financial units are appropriate measures of quantity for use by economists, they are clearly inappropriate as measures of quantity for most technological purposes. There is rarely a single multiplying factor which relates money exchanged to physical quantity particularly when the whole economy is viewed over a period of time. The difficulties in reflecting technical change using financial units have already been reviewed (see section 3.3.3.1). Not only are physical units more appropriate to a technological model but they are better able to reflect technological change since the ratio of physical inputs to physical outputs is more nearly linear than the ratio of their value. This is because distortions due to preferential pricing, financial economies of scale and differential price changes are eliminated. Ideally one hopes that the relationship between inputs and outputs for each industry would be 'stoichiometric' and thus independent of production levels, but there is still the problem of principal and non-principal production activities which is not eliminated by the use of physical units. However, a preliminary investigation indicates that the stability of input output coefficients in the energy industries is significantly improved if physical units are used (4.2).

4.2 DISAGGREGATION OF PROCESSES

A closer approximation to reality is possible when it is realised that it is through manufacturing processes rather than industries that physical quantities of inputs are related to physical quantities of outputs. Furthermore technological change or technical improvement occurs as more modern processes assume a greater importance relative to older and perhaps less efficient plant. Thus technological change can be seen not as a change in input output ratios of one industry but as a change in the relative importance of two or more processes each of which has fixed input output ratios. Industries, as defined by the Standard Industrial Classification, now cease to be relevant to the modelling of technical change and process can be adopted as the basis for disaggregation. This offers the additional advantage of still greater stability in the input output ratios since it is now possible to determine precisely in which situations true joint production occurs and where apparent joint production, when industries are engaged in more than one activity, is occurring. If it were possible to disaggregate right down to the level of processes, then it would be possible to adopt a commodity technology approach for all industries.

4.3 PROCESS ACTIVITY LEVELS

The concept of process activity levels was introduced in response to a number of observations both about input output analysis and about the requirements of a model to investigate technological change.

When physical units of measure are introduced to the transaction matrices A and B, it is no longer possible to determine the vector of total industry output ('You can't add apples and pears'). This is not serious where the technical coefficients matrix is to be calculated using only the commodity technology assumption since

$$\begin{aligned} X &= RP^{-1} \\ &= B\hat{g}^{-1}\hat{g}A^{-1} \\ &= BA^{-1} \end{aligned} \tag{4.1}$$

However, if the technical coefficient matrix is to be calculated using the industry technology procedure or by some hybrid procedure (see 4.3) then the column totals of the make matrix must be known explicitly since

$$\begin{aligned} X &= RD \\ &= B\hat{g}^{-1}A\hat{q}^{-1} \end{aligned} \tag{4.2}$$

In other words, it is no longer possible to calculate directly the matrix of technical coefficients for other than commodity technology.

A further problem with the matrix of technical coefficients is that while it can allow the calculation of total requirements to meet final demand, through the Leontief inverse, it does not allow the relative importance of differing alternative processes to be calculated or directly specified exogenously. This is a particularly important requirement of the CHP/dh model since, not only are the total commodity requirements of differing scenarios required but also a measure of the relative importance of different alternative processes.

To meet these requirements, the concept of process activity level has been developed. A unit activity level is defined by specifying the inputs and outputs at that activity level. In practice, most existing technologies are assigned a unit activity level for the level of production of that process in the data-base year. If the ratio of inputs and outputs is assumed to be constant whatever the activity level, then a new description of the Leontief-type economy (figure 4.1) can be expressed as

$$Ax = Bx + f \tag{4.3}$$

If the matrix A-B is square and non-singular then the equation can be solved for x

$$x = (A - B)^{-1} f \tag{4.4}$$

and for total output

$$q = Ax = A(A - B)^{-1}f \tag{4.5}$$

The matrix $A(A-B)^{-1}$ is the transformation matrix between q and f and is thus of the Leontief type. Comparability with the Leontief inverse can be shown by rewriting the form of equation of the transormation matrix

$$A(A-B)^{-1} = (I - BA^{-1})^{-1} \tag{4.6}$$

Thus by assigning activity levels to processes rather than to industries and then treating each process as if industry technology pertained, a Leontief inverse has been derived which is appropriate to commodity technology. This can be explained by observing that the conventional

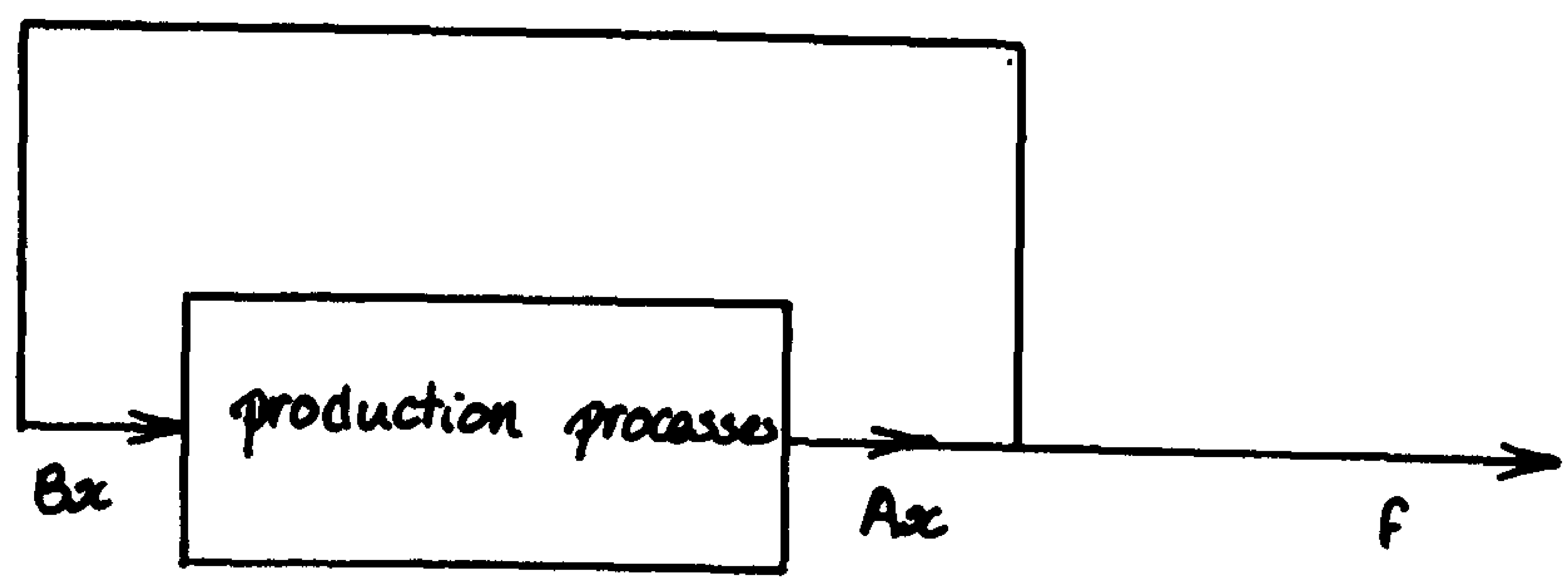

Figure 4.1 Leontief-type economy described in terms of process activity levels

derivation of the Leontief inverse based on industry technology requires the use of a market share matrix which depends upon total demand. By introducing a vector of activity levels, the individual process or industry contributions to total production can be defined independently of total production which, under industry technology, is assumed to be a constant proportion.

It is now possible to show that the calculation of x and, subsequently, q is independent of the choice of the units in which the physical quantities of commodities are expressed. Choosing an alternative description of the economy in terms of x^*, q^*, f^*, A^* and B^*, let $\hat{Z}$ be the transformation matrix whose non zero elements, z_{ii} are the conversion between the units in which commodity i is expressed so that

$$q_i = z_{ii}\, q^*_i$$

or $$q = \hat{Z}\, q^*$$

Using the alternative description

$$\begin{aligned} x^* &= (A^* - B^*)^{-1} f^* \\ &= (\hat{Z}^{-1}A - \hat{Z}^{-1}B)^{-1}\, \hat{Z}^{-1} f \\ &= (A - B)^{-1} f \\ &= x \end{aligned} \qquad (4.7)$$

Thus the activity levels are independent of the units used in the A and B matrices. Again, using the alternative description

$$\begin{aligned} q^* &= A^* x \\ \hat{Z}^{-1} q &= \hat{Z}^{-1} A\, x \\ q &= Ax \end{aligned}$$

it can be shown that q can also be calculated in terms of any appropriate units provided that

$$\hat{Z} = q\, q^{*-1} = AA^{*-1} = BB^{*-1} = \hat{f}\, \hat{f}^{*-1}$$

which is an expression of the requirement that the elements in which commodity i is expressed is consistent throughout.

4.4 RECTANGULAR MATRICES

The nature of the model described above, in which processes rather than industries become the basis for disaggregation, leads to a situation where there is an excess of processes over commodities, recorded in matrices A_d and B_d, where d denotes 'data' and a rectangular matrix. This is a particular feature of this model since the very nature of technological change supposes the replacement of one process by another. However the inverses $(A - B)^{-1}$ and $(I - BA^{-1})^{-1}$ are only defined for square matrices A and B, there are more variables x_j than equations and hence no unique solution. If the

description of the production system includes M processes producing N commodities (M > N) then three classes of possibility exist for the solution of x and q. One possibility is to devise some objective function which would optimise the system by linear programming and yield a vector of x_j's which would describe this optimised system. This is clearly a useful possibility in the present context for determining the optimum use of CHP/dh in the system and is a possible future area of investigation.* However, the use of an objective function in either a descriptive or prescriptive way, presupposes that it is possible to optimise the entire production system in some way. In reality this is only possible given perfect central control of each production process (an idealised centrally planned economy) or a perfect market, in which all producers and consumers compete equally and have perfect information.

An alternative possibility is to reaggregate M-N processes to obtain square matrices of order N. This would have the effect of reintroducing industry-based disaggregation and the only way then to model technical change would be by the gradual changing of the elements of the matrix.

*Note that considerable additional data collection would be necessary in order to follow this approach, particularly if economic criteria were to be used for the objective function.

The purpose of this model, as specified in Chapter 2 is the investigation of questions such as 'What would happen if ....'. The third possibility is to use the missing M-N rows of matrices A and B to provide a way of specifying the 'if' part of the problem. Much can usefully be learned by using the empty rows of the M x M matrix to specify the M-N relationships which will fully determine x. In practice, almost all these rows are used to specify the relationship between alternative production processes.

4.4.1 Possible relationships

Two distinct forms of constraint can be used to describe the relationship between alternative production processes. The simplest type of constraint is one where the activity level of one or more of the processes is fixed at a certain level. An alternative is to specify that the activities of two processes are in constant proportion to each other. This is effectively a reaggregation of the alternative processes and is consequently a less useful form of constraint.

Relationships between processes can be expressed in a matrix A_c which has dimensions (M - N) x M. This matrix may then be combined with the matrix $(A_d - B_d)$ to give a square matrix (A - B), the subscripts c and d denoting rectangular matrices which describe the constraints upon the processes and the transactions between the processes respectively, collected as base year data. The square matrix A-B may then be used, as before, to determine a unique solution for x. That is

$$(A - B) = \begin{pmatrix} (A_d - B_d) \\ \hdashline (\quad A_c \quad) \end{pmatrix} \qquad (4.9)$$

Where rectangular matrices A_d, B_d occur then they will be associated with the final demand and total requirement vectors f_d and q_d, both of order N. These vectors may be combined with vectors f_c and q_c which express constraint conditions and which may be combined with f_d and q_d to give vectors f and q of order M as before, so that

$$f = \begin{pmatrix} f_d \\ \hline f_c \end{pmatrix} \text{ and } q = \begin{pmatrix} q_d \\ \hline q_c \end{pmatrix} \tag{4.10}$$

and $$(A_d - B_d)x = f_d \tag{4.11}$$

and $$\begin{pmatrix} (A_d - B_d) \\ \hline A_c \end{pmatrix} x = \begin{pmatrix} f_d \\ \hline f_c \end{pmatrix} \tag{4.12}$$

so that $$x = \begin{pmatrix} A_d - B_d \\ \hline A_c \end{pmatrix}^{-1} \begin{pmatrix} f_d \\ \hline f_c \end{pmatrix}$$

$$= (A - B)^{-1} f$$

In this way rectangular matrices describing the base year commodity flows are combined with an appropriate number of descriptions for the new scenario to give a square A - B matrix which may be inverted as before to determine the x and q vectors.

4.4.2 Numerical example of process activity relationships

The operation of these constraints may best be illustrated by the use of a numerical example. Process one produces commodity one. Commodity two may be produced by process two but could be produced by an emerging technology, process three which requires a lesser input than process two. The non squares matrices A_d and B_d are:

$$A_d = \begin{pmatrix} 100 & 0 & 0 \\ 0 & 20 & 20 \end{pmatrix} \qquad B_d = \begin{pmatrix} 0 & 80 & 60 \\ 0 & 0 & 0 \end{pmatrix} \tag{4.13}$$

which are defined for the base year as the actual levels of input and output of existing processes, that is the process activity level of existing processes is one, that of not yet existent processes, zero. Thus, in the base year: $x_1 = 1$, $x_2 = 1$, $x_3 = 0$

(4.14)

Also in the base year, $f_d = \begin{pmatrix} 20 \\ 20 \end{pmatrix}$ $q_d = \begin{pmatrix} 100 \\ 20 \end{pmatrix}$

For subsequent years, with other final demand vectors, there are an infinite number of possible activity levels subject only to $(A_d - B_d)x = f_d$ and that $x_j \geqslant 0$ for all j.

This requirement expresses the observation that processes are not reversible.

Specific solutions for the vector of activity levels may be found for a number of different relationships between processes two and three as illustrated below.

4.4.2.1 Fixed activity level

In practice, this is the most useful form of constraint for modelling technological process substitution since it can be used to specify the activity level for a process in any particular year and thus allows various levels of process substitution to be explored. It may thus be used to answer questions of the type, 'What are q and x for a specified level of demand if process j produces an output of commodity i a_{ijn} in a year n. In this case a single row entry of a 'one' in column j is put in an empty row k of the constraints matrix. At any level of output a_{ijn} from process j can then be specified by entering a value f_k, to match the matrix entry $a_{kj} = 1$ in the constraint part f_c of the final demand vector where

$$f_k = \frac{a_{ijn}}{a_{ij}} \tag{4.15}$$

If in the numerical example, it is required that process three produce a specified level of commodity two then the square matrices become

$$A = \begin{pmatrix} 100 & 0 & 0 \\ 0 & 20 & 20 \\ 0 & 0 & 1 \end{pmatrix} \qquad B = \begin{pmatrix} 0 & 80 & 60 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{4.16}$$

and hence

$$(A - B)^{-1} = \begin{pmatrix} 0.010 & 0.040 & 0.200 \\ 0 & 0.050 & -1 \\ 0 & 0 & 1 \end{pmatrix} \tag{4.17}$$

$$A(A - B)^{-1} = \begin{pmatrix} 1 & 4 & -20 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{4.18}$$

If it is further specified that in a particular year process three produces 5 units of commodity two then $f_3 = 5/20 = 0.25$ and hence

$$x = \begin{pmatrix} 0.010 & 0.040 & 0.010 \\ 0 & 0.050 & -1 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} f \\ f_2 \\ 0.25 \end{pmatrix} \tag{4.19}$$

$$q = \begin{pmatrix} 1 & 4 & -20 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} f \\ f_2 \\ 0.25 \end{pmatrix} \tag{4.20}$$

This approach has some important features. In the matrix of intensities the element in the i'th row and the j'th column is the quantity of commodity i required to produce one unit of commodity j. In this case 'commodity three' is the constraint entry from matrix A_C and the elements in the third row represent the opportunity cost of the constraint, the quantity of commodity i required if $f_j = 1$. In other words if process three were to have unit activity then elements in the third row are additional quantities of commodities required compared with the state where three has zero activity. So that operating process three with activity 1 <u>saves</u> 20 units of commodity one compared with the situation when process three has zero activity.

A second and important feature of this approach to constraints is that it offers a new approach to dynamic modelling. The substitution of process three for process two may be modelled by specifying a time trajectory for the appropriate entry in the constraint part, f_c, of the final demand vector rather than the conventional approach which requires that technical coefficients have a specified time trajectory to follow a technological substitution which requires the calculation and recalculation of the inverse $(I - X)^{-1}$. By contrast, in this approach the inverse need only be calculated once which offers considerable savings in computer time (the calculation of inverses is notoriously time consuming).

4.4.2.2 Activities in constant proportion

Another form of constraint is the specification that the activities of two processes be in constant proportion. This is effectively a reaggregation of the two processes. The constraint is expressed by the equation

$$\alpha_{km}x_m + \alpha_{kn}x_n = 0$$

$$\text{or} \quad \frac{\alpha_{km}}{\alpha_{kn}} = \frac{-x_n}{x_m} \tag{4.21}$$

where α_{km}, α_{kn} are elements in the kth row of the matrix A_c and processes m and n are the processes which operate in constant proportion. In this case the corresponding entry in vector f_c is $f_k = 0$.

In the numerical example, the requirement that activity levels of processes two and three be equal ie in constant one to one proportion is expressed

$$A - B = \left(\begin{array}{ccc} 100 & -80 & -60 \\ 0 & 20 & 20 \\ \hline 0 & 1 & -1 \end{array}\right) \tag{4.22A}$$

or

$$A - B = \begin{pmatrix} 100 & -80 & -60 \\ 0 & 20 & 20 \\ \hline 0 & -1 & 1 \end{pmatrix} \tag{4.22B}$$

giving

$$(A - B)^{-1} = \begin{pmatrix} 0.010 & 0.035 & 0.100 \\ 0 & 0.025 & -0.500 \\ 0 & 0.025 & 0.500 \end{pmatrix} \tag{4.23A}$$

or

$$(A - B)^{-1} = \begin{pmatrix} 0.010 & 0.035 & 0.100 \\ 0 & 0.025 & 0.500 \\ 0 & 0.025 & -0.500 \end{pmatrix} \tag{4.23B}$$

The third column of the matrix of intensities gives the opportunity cost of producing the output of whichever process is the positive entry. The other intensities will be those which relate to the weighted average of the inputs and outputs of the fixed process.
So that

$$A(A - B)^{-1} = \begin{pmatrix} 1 & 3.5 & 20 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{4.24A}$$

or

$$A(A - B)^{-1} \begin{pmatrix} 1 & 3.5 & -20 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{4.24B}$$

4.4.3 Overproduction

Overproduction is a real possibility in specifying a final demand and the vector x must be checked to ensure that the solution does not contain negative entries. A negative entry x_j in the x vector indicates that the process j is running backwards, absorbing output to produce input.

If the production system is constrained as shown in equations 4.16, then a final demand vector such as

$$f = \begin{pmatrix} 20 \\ 15 \\ \hline 1 \end{pmatrix} \tag{4.25}$$

will generate an x vector

$$x = \begin{pmatrix} 0.6 \\ -0.25 \\ 1 \end{pmatrix}$$

which shows that process two here absorbs 5 units of commodity two produced by process three and produces 20 units of commodity one.

In a small matrix such as equation 4.16, it is easy to spot that over production will occur, since process three was constrained to produce 20 units of commodity two with no absorption by the other processes of the surplus production. However, overproduction possibilities may not otherwise be easy to spot and explicit checking is required. In this example the vector of total outputs q gives no indication that overproduction has occurred and that the specified final demand cannot be met with the technologies specified. The emergence of negative numbers in the vector x is the normal indication that some barrier exists to a particular technological option.

4.5 TREATMENT OF IMPORTS

Since it is not a purpose of this model to explore overseas trade characteristics of CHP/dh technology, the treatment of imports can be made very simple and no attempt is made to establish any trade balance. However, it is clear from discussion in the previous chapter, that any treatment of imports based on assumptions of constant import mix or a constant ratio of imported to domestically produced commodities would be an unrealistic model of reality, particularly in this instance where changes in energy technology are likely to have a substantial impact upon requirements for imported oil.

The adoption of the vector of process activity levels enables a different approach to be used in the treatment of imports and although treatment of imports is very rudimentary in this model, this represents an interesting possibility for other users of input-output analysis. 'Importing commodity i' may be seen as a process which may be entered among the other processes. There are zero entries in the corresponding column of B. Where imports are the only source of a commodity then the importing process will behave as any other. Where the imported commodity is in competition with the domestically produced commodity then an entry in one row of the constraints matrix will normally be required to 'decide' how production is allocated between the domestic and the importing source. This not only enables the effects of (say) import controls to be explored but it is an important part of the learning process to see where <u>technological</u> options exist.

4.5.1 Total imports vector

Quantities of imported commodities may be generated by the model by use of an 'imports flag vector'. This is simply a vector set up as the model is constructed whose elements are zero, except for the elements v_j where j is an importing process; v_j is equal to one. The vector of imported commodities u is obtained by use of equation 4.26

$$u = \hat{A}vx \tag{4.26}$$

The vector v has the effect of selecting the importing processes from the matrix A.

4.5.2 Numerical example

In the model described by equations 4.27 below process three is the importation of commodity two in competition with domestic production by process two. It is proposed to investigate the effects of allowing twice the present quantity of commodity two to be imported in a situation where there is also an increase in final demand for commodities one and two.

$$A = \begin{pmatrix} 3 & 0 & 0 \\ 0 & 6 & 3 \\ \hline 0 & 0 & 1 \end{pmatrix} \quad B = \begin{pmatrix} 0 & 1 & 0 \\ 2 & 0 & 0 \\ \hline 0 & 0 & 0 \end{pmatrix} \quad f_0 = \begin{pmatrix} 2 \\ 7 \\ \hline 1 \end{pmatrix} \tag{4.27}$$

a_{33} is the constraint variable.

The new final demand is

$$f = \begin{pmatrix} 3 \\ 8 \\ \hline 2 \end{pmatrix} \tag{4.28}$$

f_3 is the variable which specifies that the activity of the importing process is doubled. The imports flag vector associated with matrices A and B is

$$v = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \tag{4.29}$$

and while matrices A and B retain their present formulation v does not vary, being dependent only on the allocations of processes to columns. From equation 4.4

$$x = (A - B)^{-1}f$$

$$= (A - B)^{-1}\begin{pmatrix} 3 \\ 8 \\ 2 \end{pmatrix} \qquad 4.4$$

and hence

$$x = \begin{pmatrix} 1.25 \\ 0.75 \\ 2 \end{pmatrix}$$

The vector of <u>total</u> production q is given by equation 4.5

$$q = Ax$$

$$= \begin{pmatrix} 3.75 \\ 10.5 \\ 2 \end{pmatrix}$$

It should be noted that since matrices A and B now include importing, q might more accurately be regarded as a vector of total availability. The vector of imports is given by equation 4.26

$$u = A\hat{v}x \qquad (4.26)$$

$$= \begin{pmatrix} 3 & 0 & 0 \\ 0 & 6 & 3 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1.25 \\ 0.75 \\ 2 \end{pmatrix}$$

$$= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 3 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1.25 \\ 0.75 \\ 2 \end{pmatrix}$$

$$= \begin{pmatrix} 0 \\ 6 \\ 2 \end{pmatrix}$$

It should be noted that the value of the constraint also appears in the vector of imports. The vector of domestic production can also be obtained, if required, as the difference between q and u, in this case:

$$\text{domestic production} = \begin{pmatrix} 3.75 \\ 4.5 \\ 0 \end{pmatrix}$$

4.6 FUNCTIONAL COMMODITIES

Technological change may involve commodity substitution as well as process substitution. For example the delivery of hot water to domestic premises for district heating will displace an equivalent quantity of gas, electricity, oil or solid fuel.

The purpose of supplying gas, electricity, etc. to homes is not that householders want to own electrons or lumps of coal (as pointed out by Chapman (4,4)). Rather these commodities are purchased so that houses may be warmed. Given the right equipment, these fuels or energy carriers are fully substitutable, to a first approximation. That is to say that purchasers are indifferent to which energy carrier they purchase provided they can achieve the desired standard of warmth.

The concept of 'useful energy' is well established as a basis of comparability for energy carriers and is used in this model as a commodity in its own right. In particular, it is used under the name low grade heat, a functional commodity for which there is a final demand.

There are a number of processes, both centralised and those practised the home, which generate heat using a variety of inputs. In the present instance, the substitution of the CHP station for the domestic heating appliance is of interest. By allowing the definition of commodity to include low grade heat, and allowing 'process' to include processes carried on by final demand sectors as a means of utilising its purchases, the commodity substitution of a new product (such as hot water) for part of final demand's purchases (of energy carriers) becomes a form of process substitution which can be investigated using appropriate constraint forms.

4.7 STRUCTURE AND DATA

It is appropriate to review at this stage how closely the model described here meets the objectives set out in section 3.1.3 above.

The principal attraction of the model described here is its simplicity, being based solely upon the equation

$$Ax = Bx + f \tag{4.3}$$

which describes the relationship between commodities and processes. This equation contains a number of inbuilt assumptions about processes which should be made explicit. The principal of these assumptions is that inputs and outputs are linearly related and that their ratio is independent of process activity level. A secondary assumption is that production is demand driven. This is equivalent to saying that there are no processes producing purchasable commodities which are not immediately transferred to demand. The meaning of this assumption becomes clear when the example of the relationship between the coal industry and the electricity industry. The assumption means that the activity level of the coal industry will be strongly influenced by the activity level of the electricity industry, its principal customer, and that over the course of the database year the purchases by the electricity industry of coal will be determined solely by their requirement for coal in that year. In practice this may not be strictly true since coal is a storable commodity. A consequence of recent policy has been a large increase in the stocks of coal kept at power stations and during the acquisition of these stocks, the linear relationship between coal purchases and electricity output will be modified. Although the database year (1977) was one in which no major stock change took place in the electricity industry, this example illustrates the problems of modelling industries or processes which acquire and deplete substantial stocks. Other subsidiary assumptions are that purchasers are indifferent to sources of supply and that aggregated commodities are undifferentiated.

The linearity assumption is fairly sound if disaggregation is based on processes. The major exception is electricity generation where the type and quantity of input per unit of output is strongly dependent upon the instantaneous demand on the electricity system. In other words, the electricity industry does not even offer the simplicity of inputs being dependent upon annual demand. A method of dealing with this non-linearity is described in Chapter 7.

The simplicity of the model described in equation 4.3 means that the model user has the same access to the structure of the model as the model builder; very few relationships are not explicit. Feedback loops, inter-process dependency and final demand dependency are all represented purely by data entries in the A_d and B_d matrices. Technological options are all made explicit by the requirement to specify constraints of various sorts in the A_c matrix.

4.7.2 Detail

The simplicity of the model in terms of its basic equation does not require any sacrifice of detail since a very large number of processes and commodities can be described within the basic framework. The major limitation in detail is the computational capabilities of the computer and the availability of reliable process data for high levels of disaggregation. The criterion for disaggregation are discussed in the next chapter.

A guideline for the appropriate level, as discussed in the previous chapter, is that the level of disaggregation should be the minimum required to provide an answer to the problem posed. This somewhat tautological guideline does require that detail should not be sought for its own sake since models (even simple ones like that described here) can rapidly generate incomprehensibly large quantities of data. Furthermore, in models where data provide the principal descriptions of relationships between processes, the quantity of data required to describe these relationships is large and a requirement for too great a level of detail will quickly strain data beyond the level of obtainability.

The requirement that the model be capable of use for other technological change investigations depends upon the level of disaggregation.

4.7.3 Data requirements

The activity levels model which describes the production and absorption of N commidity by M processes will require a total of M x N data items for the matrix A - B. Of these the positive entries will appear in the matrix A, and the negative items in B, ie

$$\text{if } (a-b)_{ij} > 0 \;,\; a_{ij} = (a-b)_{ij}$$
$$\text{if } (a-b)_{ij} < 0 \;,\; b_{ij} = |(a-b)_{ij}|$$

(In practical terms it is generally easier to construct matrices A and B together in this way, since the matrix A - B is easier to construct, giving a clearer picture of commodity flow which is easier to check for consistency).

In practice, a very large number of the entries in both A and B will be zeros since at practical levels of disaggregation, few processes will produce more than a small number of commodities or require more than a few inputs.

Nonetheless, identifying all the elements a_{ij} and b_{ij} is a major task (even if many of them are zeros) since the model cannot use incomplete matrices.

It would be possible to specify all processes, existing or not, in terms of an arbitrarily specified level of output for which the process activity level would be one, but comparability with a known and experienced set of conditions, such as those of a particular year, gives considerably more meaning to data describing process activity levels and commodity requirements. The data used in the model is thus based on 1977 commodity flows. Process activity levels for these processes, not in existence in 1977 (such a large scale CHP/dh) are specified in terms of some suitable level of output (100 Mtherms/year) and assigned an activity level of zero.

Literature on the management and acquisition of the large data bases required for input output studies is very sparse and seems to be a neglected area of academic exchange. This is particularly surprising when it is observed that in data-hungry and data-dependent models such as input output models the availability and quality of relevant data may be a strong influence on the type of modelling which it is possible to undertake. Highly developed strategies for handling data bases, such as those devised by Karni et al (4.5), in connection with the OMER model of Israel's energy use have not been used in this model, since there was not reason to suspect that the data base would get 'out of hand'. However, many of the general conclusions drawn by Karni have proved valuable. In particular, he draws attention to the need to document not only the original data but also the procedures by which the data is rendered compatible with the model. This procedure has been followed as far as possible in this project (see Appendix 5).

4.7.4 Error propagation

There are two main sources of possible error which need to be considered with the matrix formulation adopted. These errors arise from innacuracies in the data whether through inherent inaccuracy or through incorrect entry into the matrix or from the second source, errors due to computer rounding of numbers - this can be a major source of inaccuracy in large matrix calculation unless specific steps are taken to avoid it.

4.7.4.1 Data error

Data used in the matrix is used on the basis that it is the best available. However, data collected nationally on a number of different bases and then adjusted to fit the formulation of the A and B matrices, is inevitably slightly degraded. It is thus important to establish the extent to which the calculated vectors q and x and the matrix $A(A - B)^{-1}$ are sensitive to error in the data. The absolute magnitude of the errors can be found quite simply by calculation.

Let A and B be the make and absorption matrices constructed from data and appropriate constraints and let x be the vector of process activity levels calculated for an exogenously specified final demand vector f. However, A, B and x are only approximations to the actual but unknown matrices A*, B* and x*.

For convenience of presentation, let $A - B = C$ and $A^* - B^* = C^*$.

Thus $(A - B)x = f$ and $(A^* - B^*)x^* = f$ (4.27)

or $Cx = f$ and $C^* x^* = f$ (4.28)

and hence $Cx = C^*x^*$ (4.29)

C contains an error and differs from the true values by ΔC. ΔC is a matrix of errors of unknown magnitude. x similarly contains errors of magnitude Δx as a result of calculation using the erroneous C. Thus, by definition

$$C = C^* + \Delta C \tag{4.30}$$

$$x = x^* + \Delta x \tag{4.31}$$

$$Cx = C^*(x - \Delta x)$$

$$\therefore\ C^{*-1}Cx = x - \Delta x$$

$$\begin{aligned} \therefore \quad \Delta x &= x - C^{*-1}Cx \\ &= [I - (C - \Delta C)^{-1}C]x \\ &= [I - (I - C^{-1}\Delta C)^{-1}]x \\ &= (I - \Delta C^{-1}C)^{-1}x \end{aligned} \tag{4.32}$$

Thus the absolute value of the errors in x will be proportional to x and will be minimised by a large absolute value of A - B.

In practice, data error will arise as a consequence of two effects. Firstly, the small errors potentially present in each data item will affect the results for x and q and secondly, the unwarranted inclusion or the exclusion of individual data items will give misleading results. In the first case the magnitude of the error can be expressed as a single figure by comparing the difference between the sums of the squares of all the elements in the calculated vectors with those of the correct vectors.

For the second case, an indication of the effect upon x of individual matrix entries can be determined from the consideration of one row of the matrix (A - B) = c.

$$\sum_j c_{ij}\, x_j = f_i \tag{4.33}$$

The relationship between x_j and the element c_{kl} can be determined by differentiation

$$\sum_j \left(c_{ij} \frac{\partial x_j}{\partial c_{kl}} + x_j \frac{\partial c_{ij}}{\partial c_{kl}}\right) = \frac{\partial f_i}{\partial c_{kl}} = 0 \tag{4.34}$$

for all rows except row k, $\partial c_{ij}/\partial c_{kl} = 0$

so that

$$\sum_j c_{ij} \, \partial x_j/\partial c_{kl} = 0 \qquad (i \neq k) \tag{4.35}$$

for row k, $\partial c_{ij}/\partial c_{kl} = 0$, except for the l'th element for which

$$\partial c_{ij}/\partial c_{kl} = 1 \qquad (i = k, \; j = l)$$

so that for the k'th row

$$x_k + \sum_j c_{ij} \, \partial x_j/\partial c_{kl} = 0 \qquad (i = k) \tag{4.36}$$

Equations 4.35 and 4.36 are matrix equations giving

$$C.d = e$$

Where d is the vector whose j'th element is $\partial x_j/\partial c_{kl}$ and e is a vector whose only non-zero element is the k'th whose value is $-x_l$. The way in which each value of x_j depends upon the value of the element c_{kl} can then be determined by use of the inverse.

$$d = C^{-1}e \tag{4.37}$$

The vector e has the effect of selecting out the k'th column of the inverse so that the rate of change of x_j with one of the elements c_{kl} is expressed as

$$\frac{\partial x_j}{\partial c_{kl}} = -(C^{-1})_{jk} x_l$$

where $(C^{-1})_{jk}$ is the j'th element in the k'th column of the inverse of matrix C.

It should be noted that the absolute magnitude of $\partial x_j/\partial c_{kl}$ is dependent upon the value of x_l and that the magnitude of the errors caused by defective elements c_{kl} will increase as the activity level of process l increases. Since this is most likely to occur in processes where new processes are replacing old ones, it is these processes where elements in the make and absorption matrices should be specified with particular care.

4.7.4.2 Computational error

The solution of linear equations by computer methods requires large numbers of individual calculations and, if the equations are 'ill conditioned' for the solution of the vector x, then errors will propagate very rapidly and the solutions may well be nonsense. A discussion of this point and others relating to solution of matrix problems is to be found in Fox and Mayers (4.6). No rigourous analysis of computer error propagation has been done for this model, instead an experimental approach has been adopted to determine whether an acceptable level of accuracy is attainable in inverting the matrix.

To do this, matrix of residuals was calculated

$$E = I - (A - B)(A - B)^{-1} \tag{4.38}$$

where $(A - B)^{-1}$ is the 'computer inverse' of the specified matrix $(A - B)$. The error in the x vector Δx now becomes

$$\Delta x = Ex \tag{4.39}$$

It was found that 'single point accuracy' was sufficient to give results within 0.001% of the expected value for matrices of up to order 60. This was adequate for the project since it is possible to identify single row entries and invert only a reduced matrix. This procedure carries the additional advantage of saving CPU time.

4.8 CONCLUDING REMARKS

The model as structured gives simple and comprehensible comparisons between a known scenario (ie the situation in 1977) and postulated CHP/dh scenarios at unspecified dates in the future. The generated scenario is in the form of process activity levels, indicating the relative importance of the process described, and the total requirements for commodities, imported and otherwise. These are generated in response to a set of specified assumptions and policy statements which are specified in the form of constraints. Because the model does not contain these constraints or generate them during a model run, it is possible to see exactly the source of any interesting or counter intuitive results; thus model operation as well as model building becomes a learning process. An additional advantage of non-internal constraints is that if a specified final demand or exogenous constraint runs up against a barrier and 'fails' the specified scenario, then it is immediately obvious how unacceptable the chosen scenario is. The transparent model makes this very clear and allows the scenario to be re-specified appropriately.

An example of a typical technological change investigation is given for a small economy in Appendix 4.

5. DATA ORGANISATION AND SOURCES

In a model of the type described in the previous chapter, where all relationships are described by the presence or absence of a data entry in the matrices, it is appropriate that explicit attention be given to the sources of the data. It is also important to establish the domain to which the model refers and to make explicit both the boundary and the nature of interactions across the boundary.

5.1 STUDY BOUNDARIES

The model devised for this project describes energy flows (in particular) in the United Kingdom. It does not deal with processes which are carried on outside the UK. The products of these processes appear in the model as a consequence of the activity of importing that particular product. Similarly total requirements vectors refer only to the total requirements for goods within the UK. The reasons for taking this decision are several. Firstly the UK is the domain in which energy policy primarily operates and national government is the level at which decisions are made. Although there is considerable interest by Local Authorities in intervening in energy policy issues, it is nonetheless at national level that decisions about electricity generation, coal production and oil production are made. The present study was stimulated by the ideas and debate which arose out of the publication of Energy Paper 20 (5.1) and to a lesser extent Energy Paper 35 (5.2). These two took as their domain the whole of the United Kingdom, treated as a geographically homogeneous entity. This study follows that lead. A post hoc reason for adopting the UK as the domain of the study is that data is conveniently available in a suitable form for the UK. Data collected for alternative systems (eg Europe, regions etc.) is considerably more sparse. The availability of good quality data is especially significant when the data requirements of the model are so important.

5.2 CRITERIA FOR DISAGGREGATION

Consistent with the minimalist approach adopted in the modelling of the UK energy system and a desire to avoid the 'deadly sin of hypercomprehensiveness' (see Lee 5.3) the working criterion for deciding to what level industries and processes within the UK should be disaggregated may be stated as follows. The level of disaggregation should be the minimum necessary to show all the important effects of a particular set of technologies, consistent with the linearity assumption. This statement begs a lot of important questions. In particular, it leaves unresolved any discussion of what constitutes an 'important effect', of which, in any case, it supposes pre-knowledge. This is another striking example of how a model can inform more by the construction than by use. By examining the preliminary list of processes and considering the exchange between them of the preliminarily listed commodities the level of understanding of the effects of each technology upon the others is significantly advanced. A number of examples are mentioned in Chapter 6 which describes the pilot study. In practice, the level of disaggregation is such that the principal energy producing technologies are disaggregated to process level while most of the remaining industries are aggregated together. Iron and steel production and petrochemicals are disaggregated from other manufacturing industry since they are principal consumers. The commodities and processes used for the pilot study are listed in Table 5.1. This list is also the basis for the fuller study in which special treatment is given to electricity and to the electricity production process. A number of modifications arising out of the experience of the pilot study were also incorporated and are discussed in the next chapter. The points of interest in this disaggregation set are discussed below.

Table 5.1 Commodities and Processes for pilot study

Commodities	Processes
1 fuel gas	1 North Sea gas production
2 coal	2 Synthetic natural gas production
3 coke	3 Coal mining
4 crude oil	4 Coke ovens
5 refined oil	5 North Sea oil production
7 electrccity produced	6 Crude oil importing
8 electricity delivered	7 Oil refineries
9 petrochemicals	8 Refined oil importing
10 iron and steel	9 Gas turbine power plant
11 other goods and services	10 Coal fired power stations
12 transport	11 Oil fired power stations
13 commercial low grade heat	12 Nuclear power stations
14 domestic low grade heat	13 Electricity transmission
15 water-borne heat for distribution	14 Petrochemical industry
	15 Iron and steel production
	16 Other manufacturing and services
	17 Transportation
	Commercial properties
	18 heating - gas fired
	19 - coal fired
	20 - coke fired
	21 - oil fired
	22 - electrical
	23 Domestic heating - gas fired
	24 - coal fired
	25 - coke fired
	26 - oil fired
	27 - electrical
	28 District heating - diesel CHP
	29 - coal CHP I
	30 - coal CHP II
	31 - coal CHP III
	32 - nuclear CHP I
	33 nuclear CHP II
	34 - gas total energy
	35 - diesel industrial total energy
	36 - coal fired HOBs
	37 - oil fired HOBs
	38 - gas fired HOBs
	39 Heat distribution to commercial sector
	40 Heat distribution to domestic sector

5.2.1 Gas production processes

Gas is a principal energy commodity in the UK, relevant to the present study both as an input to technologies likely to be displaced by CHP (domestic and commercial heating, gas turbine power plant) and as an input to some of the CHP/dh technologies. Two production processes are described; the 1977 production process, extraction from the North Sea fields; and a potential future source of gas, the synthetic natural gas production process. This is included because Energy Paper 20 sets a scenario in which CHP/dh becomes a significant contributor to the fuel economy at the same time as North Sea gas stocks become depleted.

5.2.2 Electricity production and transmission

In the full scale study, electricity and electricity production are treated on a totally different basis to that used in the pilot study (see Chapter 7). Indeed one of the aims of the pilot study was to test the model without the encumberance of the large model of the electricity production process. In the pilot study power stations were merely distinguished by fuel input type to reflect, albeit crudely, the different roles that gas turbines, coal and oil plant, and nuclear stations play in the production of electricity.

Electricity transmission is distinguished as a separate process for two reasons. Firstly, the transmission of electricity is not 100% efficient. To attribute the losses to the production processes would produce misleading results. But to build in the idea that consumers somehow 'buy the losses' in a direct way would also give misleading comparisons with other fuels. The adoption of 'electricity transmission' as a process by which 'electricity generated' is (inefficiently) converted into 'electricity delivered' carries the not inconsiderable advantage that by so doing, the calculated activity level of the process gives an activity level for electricity production as a whole.

5.2.3 Iron and steel and petrochemicals

These two sets of production processes are disaggregated from other manufacturing industry since they are major energy consumers (or, more strictly in the case of petrochemical production, consumers of energy products) and their output is found in the pilot study to be a major influence in the total requirements for energy products). Their separate identification is not strictly necessary for the present study since, like transport and other goods and services, the demand for the commodities is held at 1977 levels in all the scenarios investigated. However, their inclusion was necessary for calibration of the model since the demand for iron and steel and petrochemicals has changed dramatically since 1977 (changing economic fortunes!) The documenting of the iron and steel industry will become significant when the capital requirements of a CHP/dh programme are investigated (see Chapter 9, section 9.3.1.3).

5.2.4 Other manufacturing and services

All the remaining intermediate sectors of the economy are aggregated together in a single process producing 'other goods and services'. This aggregation means that the size of the matrices is reduced and unnecessary detail is eliminated. The internal feedback loops in these sectors (eg that between cereal processing (animal feed) and agriculture grain)) are not identified as being of concern to this study.

The sector as defined implies a linearity between the inputs specified (mostly energy products) and the output (goods and services). In reality, since goods and services are not homogeneous the relationship between the energy inputs and the output will not be linear, either in quantity or quality. However, the aggregation of these processes into a single process is merely an explicit recognition of the 'all other things being equal' nature of the comparison of CHP/dh scenarios. This sector also includes all imports not elsewhere specified.

5.2.5 Transport

Transport, which includes all non-personal transport, is included solely for the purposes of calibration. It too takes the 'all other things being equal' approach to the aggregation of rail, air and road transport.

5.2.6 Commercial and domestic heating processes

Although commercial heating processes might normally be treated as intermediate production, it is unusual to have domestic heating so treated. The reason for this is explained elsewhere (see Chapter 4, section 4.6). The separate fuel inputs identify separate heating processes so that disproportionate displacement of one fuel by CHP/dh can be investigated in the future. This will allow the investigation of more realistic CHP scenarios (see Chapter 9 section 9.3.1.1). Commercial and domestic heating processes are distinguished from each other since their efficiencies are different.

5.3 DATA SOURCES

5.3.1 Database year

The matrices A and B describe the production, flows and purchases of commodities in the form of a 'snap-shot' of one year. In other words the element of a_{ij} in the matrix A represents the quantity of commodity i produced by process j <u>in one particular year</u> (where process j is an existing process). Thus for one real year for which data is known

$$\sum_j a_{ij} x_j - \sum_j b_{ij} x_j = f_i$$

where x_j is one for all existing processes and zero for all future processes, not operating in the database year. It is clear then that the elements a_{ij} and b_{ij} relate to the actual experience of one particular year in the UK in the case of existing technologies or to operation at some arbitrarily defined level for an as yet non-existent process (such as CHP/dh).

In practice the selection of a particular year as the data base year for which, by definition

$x = (A - B)^{-1} f = i$ for existing processes is constrained by a number of considerations. Firstly the data base year should be a 'typical' year capable of representing the present day state of technology. Its function in this project is as a basis for comparison of a number of CHP/dh scenarios and so represents a state of technology from which CHP/dh is absent. The choice of a database year which is as recent as possible allows the comparison to approximate to that with 'the present'.

The most recent year for which adequate data was available to this study was 1977. Data for more recent years is either unavailable, because of the time it takes to assemble and collate the data, or it is still subject to retrospective adjustment as better quality data becomes available. This phenomenon is frequently encountered in published data, where comprehensive, stable data is unavailable until several years after the year to which it refers. 1977 is thus adopted as the data base year for assembling process data for the make and absorption matrices.

5.3.2 Data

The production and use of energy in the United Kingdom is richly and comprehensively documented. Other data is somewhat sparser and more difficult to obtain. The make and absorption matrices can be broken down into the sub-sections indicated in Tables 5.2.A and 5.2.B. The data entries in each of these sections have different characteristics and come from different sources; some are easier to find than others.

5.3.2.1 Energy production sectors

The quantities of energy produced by the energy producing sectors of the economy are well documented in official publications such as the Digest of United Kingdom Energy Statistics, published annually (5.4). The interactions between the energy processes, as manifest by the sales of one energy product for the production of another energy product, are also well documented in the Digest. Less well documented are the purchases of non-energy products for the production of energy. They typically account for a very small part of the expenditure of these industries and also, typically, account for only a very small part of the output of the non-energy producing sectors. Principal data items can be found in the 1974 Census of Production and where necessary are 'scaled up' to 1977 levels of production.

5.3.2.2 Heating processes

Data breaking down quantities of fuel purchased for heating to any other purpose, is not available from 'official' sources. However, an extensive study by IIED explicitly examined the energy requirements for heating purposes and their well documented study (5.5) proved a useful source of data about both domestic and commercial heating processes. Seasonal demand for heat is calculated (data not being directly available) using a sinusoidal relationship between season and low grade heat requirements.

Table 5.2A Data blocks for make matrix

A	energy production	heating processes	non-energy production
energy products	energy production		
low grade heat		low grade heat production	
non-energy products			non-energy production

Table 5.2B Data blocks for absorption matrix

B	energy production	heating processes	non-energy production
energy products	inputs to production of secondary fuels (eg electricity)	energy inputs to heating processes	energy inputs to other production
low grade heat			heating inputs to other production
non-energy products	non-energy inputs to fuel production		non-energy inputs to other production

5.3.2.3 Non-energy production sectors

The determination of the total quantities of non-energy production is not easy. The basis upon which the energy and heating processes are disaggregated, means that it is not easy to determine data for the remaining sectors. This problem has been by-passed by measuring non-energy production in units of '1977 production'. The alternative approach of adopting monetary units as a measure of the combined quantities of diverse products would require that the total production of the UK production system be individually summed, or that the value of transactions including energy or heat be determined, and subtracted from the total value of UK output. Neither of these options is attractive either in terms of effort required nor in the accuracy of the data that would result, especially when the device of using '1977 production' as a measure of output is an adequate solution to the problem.

The energy inputs required for non-low grade heating processes have to be separated from those for heating purposes, which appears as input to commercial heating processes.

A fully documented account of the actual data entries and their sources and derivation is given in Appendix 5.

5.3.3 Units

Flows of energy are recorded such that all the entries in any given row of the matrices A and B have the same units. It is shown in Chapter 4, section 4.3, that the calculation of x is independent of the units in which a_{ij} and b_{ij} are expressed (provided they are the same for all j). The units selected to record quantities of each fuel are those commonly used in energy policy discussions ie GWh of electricity, million tonnes of coal, etc. Because of problems associated with the concept of overall energy intensity, it was not thought necessary to use common units for all fuel types, as would be necessary for calculation of energy intensity.

5.3.4 Electricity data entries

The aggregation of a number of commodities into a single row entry is the expression of an assumption that all the aggregated commodities are homogeneous, interchangeable and equally available to all consumers. This is not strictly true of electricity in the UK. Electricity generated in England and Wales by the CEGB is not directly available to Scottish consumers. Similarly, electricity generated by the SSEB and NSHEB in Scotland is not available in England, except by specific exchange agreement between the generating boards when peak load sharing procedures are implemented. The Northern Ireland Electricity Service operates quite separately from the mainland generation boards and has exchange facilities with the Irish electricity generation system. Thus an increase in demand for electricity in a part of the United Kingdom served by one generating authority could not be met by an increase in the activity of the generating plant of a Board serving another part of the UK, or indeed by an overall increase in the activities of all the Boards. In this sense electricity is not homogeneous; 'Scottish Electricity' and 'English/Welsh electricity' are not interchangeable. This distinction would be of no relevance if the electricity generation systems were broadly similar. However, the CEGB system is dominated by nuclear and fossil fuelled steam plant, the Scottish system contains a substantial element of small hydro electric plant and the Northern Ireland system by oil fired plant. Despite this problem however, and because the CEGB account for 86.6% of all UK electricity production, electricity has been treated as though all the generating boards were fully integrated and interconnected (see Chapter 7).

5.3.5 New processes

Technological change, as described in this project is the change in relative activity level of two or more processes. The particular technological change in question, the displacement of traditional heating sources by CHP/dh means that data for CHP/dh processes, unavailable in the 1977 'snapshot', must be provided for the model. In addition, data is supplied for a future process producing synthetic natural gas from coal. Data for eleven separate CHP/dh and HOB/dh technologies together with that for a 'CHP programme' of a number of technologies acting together are specified.

5.3.5.1 CHP/dh technologies

The specification for these is loosely based on the technologies specified in Energy Paper 20, appendix 2. They are recorded in Appendix 5.

The technologies are chosen on the basis that they will maximise available knowledge and understanding rather than to examine realistic CHP/dh scenarios. Any 'realistic' CHP scenario will include more than one CHP/dh technology.

5.3.5.2 SNG production

While it is not the intention to investigate technologies other than CHP/dh, nor to investigate comprehensive scenarios, it is nonetheless thought likely that a large CHP/dh installation programme could not be completed before North Sea gas reserves were depleted. A single coal to gas conversion process has been included in the matrices to reflect this since SNG production would have such a radical effect on the energy supply situation.

5.4 NON-LINEAR PROCESSES

Although most processes can be represented in terms of a linear relationship between inputs and outputs, there are a number of examples of processes which cannot be realistically represented in this way. The specific example of electricity generation is dealt with in Chapter 7. Oil refineries are also non-linear in operation. The output mix from oil refineries can be adjusted to respond, within limits, to demand for the various oil refinery products. This is done by varying the boiling point ranges included in each 'cut'. A procedure has been developed by the author to represent this variation in output which, although not used in this project (the range of variability being fairly limited and not significant at the level of disaggregation used), represents a general approach to the problem of variable output or input.

Another example of non-linearity (this time in input requirement) would be that of steel production where varying proportions of pig iron and scrap steel may be used as inputs to the steel production process.

5.5 CALIBRATION AND DATA CHECKING PROCEDURES

The importance of calibration and/or checking procedures is, according to Meadows (5.6), frequently underestimated. However, it is also important to establish exactly what the aims of a calibration and checking exercise are before embarking upon the data collection and matching procedure which is required for 'other years' comparisons. Unlike dynamic models, describing the progress of a technology through time, this model does not require detailed calibration in the time domain. Thus the aim of a calibration and checking procedure can be stated as being:

(a) to establish whether input output ratios found for 1977 can be adequately used to represent those of altered states of technology

(b) to establish whether there are additional undocumented processes which materially influence the total flows of commodities.

The disaggregation of production on a process rather than an industry basis is specifically designed to minimise variation in input output ratios in the matrices. Although all processes show improving input output ratios through time, once established, the change is slow enough to be insignificant within the context of this study. The other principal source of variation in input output ratios is that of 'economies of scale' where input output ratios decrease with increasing production levels.

Major changes due to a change in process can be dealt with by fulfilling the second aim of calibration and checking. Variations arising from change in overall production level are difficult to deal with theoretically since, by definition, the matrix format of the table assumes a linear relationship between input and output at all levels of production. However by examining the characteristics of the disaggregated processes, it is possible to be assured that in the present case input output ratios are unlikely to vary by more than approximately 5% (4.2), either because economies of scale are not a major feature of the process or because production levels do not vary significantly in the scenarios under test. Electricity production is as always an exception, dealt with in Chapter 7. 'Learning' is relatively slow in mature processes and therefore of no great significance in this study. It may, however, be a significant feature in the early life of new and future processes, especially when the overall production level is low. Both SNG production and CHP/dh are likely to be affected by this but calibration and checking will not of course reveal this effect. It is sufficient merely to note the liklihood of its appearance in assessing the two technologies.

The presence of undocumented processes in the system was investigated by specifying a state of technology and demand based on 1980 data. However, a post-hoc calibration in the strict sense is not possible with a model of this kind and the 'forecasting a past year' approach is neither appropriate nor really possible since policy in previous years operated in ways which are not as explicit as required for precise specification of constraints. Nonetheless a final demand vector for 1980 was obtained from 1980 data and the corresponding vector of total demand, q, was calculated and compared with 1980 data. Insofar as the accuracy of the data allowed, this exercise showed that each q_i lay within 4% of the expected value with the exception of those related to iron and steel production. Between 1977 and 1980, steel imports became a significant part of steel supplies as the activity of the domestic steel industry declined rapidly. Imports of steel in 1977 were too insignificant to be separately disaggregated but are included as a separate process in the full scale study.

5.6 PILOT STUDY

When it became clear that representation of the electricity industry's operations would be a significant part of the model, it was decided to do a pilot study to thoroughly check the operation of the non-electricity sectors of the model and to obtain indications of the likely significance of each sector in a future which included CHP/dh. This study together with a discussion of its findings is reported in Chapter 6.

6 PILOT STUDY

6.1 PURPOSE

A pilot study was undertaken in order to check and test those parts of the matrices concerned with the non-electricity descriptions of the production system (including the heating processes and the CHP/dh processes) and a linear approximation of the electricity production system.

The description of the production system in terms of 40 production processes and 15 commodities (see Table 5.1) leaves a requirement for a 25 x 40 constraints matrix to fully define the x-vector and to square the matrix.

The pilot study was designed to fulfil four main purposes.

Firstly, the pilot study would check that the tables, as formulated, would enable a unique solution x to be found for any given final demand vector f; in other words, a check that the full matrix A - B is non singular and therefore has a unique inverse $(A - B)^{-1}$.

Secondly, and relatedly, the pilot study would enable the identification of elements in the matrix A - B which have the effect of constraining the activity levels of different processes in an unnatural way.

The third purpose of the study was to enable the calibration/checking procedure described in section 5.5 of Chapter 5 to be carried out.

Finally the pilot study was to provide indications of the likely consequences of introducing CHP/dh technology, with possible indications of the areas which might fruitfully be investigated in the full scale study and in future studies.

Tables A and B were compiled using data derived in Appendix 5 together with data for a possible SNG synthesis process using coal as an input.

6.2 CONSTRAINTS SPECIFICATION

A matrix description A - B of transactions in the UK in which there are 40 processes producing 15 commodities requires 25 constraints in order that $(A - B)x = f$ can be solved for x, the vector of activity levels. An examination of the list of commodities and the list of production processes (Table 5.1) gives an indication of where constraints are needed in order that a unique inverse exists. For practical reasons it was found convenient to mix the rows of the commodity matrices and the constraints matrix.

6.2.1 Fuel production constraints

The first constraint required is one that will relate the production processes for natural and synthetic natural gas which are treated as identical products in this study. The constraint form used in the study was that which constrains the activity level of a process to one particular level, in this case either zero SNG production or zero North Sea production. Other constraints required are those determining the source of crude oil (N. Sea or imports) and those determining the source of refined fuel oil (refineries or imports). Since neither of the crude production 'processes' requires process inputs (those for N. Sea production being negligible), there is no resource implication for either source choice. Refinery operation was constrained to its 1977 level for this study. There are a total of three constraints required for the non-electricity fuel production of 5 fuel commodities.

6.2.2 Electricity production constraints

Three constraint specifications are required to determine the activity levels of the four electricity production processes which are characterised by fuel input type. No attempt was made in the pilot study to model all the relevant features of the electricity production system. Instead, it has been assumed that changes in the demand for electricity for heating purposes will have no effect upon the magnitude of demand for baseload electricity and that the requirement for fast pick-up plant will also be unchanged. In other words, it has been assumed that only the operation of middle order plant will be affected by the presence of CHP/dh and HOB/dh in the system. The quantities of electricity required from baseload and peaking plant will remain unaffected. This is only a first approximation; it is, for example, true that approximately 2.47 GW of baseload demand (21.6 TWh per annum) is attributable to domestic hot water demand. It is further assumed that all middle order plant affected will be coal fired, a crude approximation upon which the full scale study makes a substantial improvement.

6.2.3 Low grade heat constraints

A total of eight constraint specifications are required to determine the relative activity levels of the low grade heat production processes which are again specified by fuel input type. Since commercial low grade heat and domestic low grade heat are described as distinct commodities, four of the eight constraints pertain to each of the commodities.

The scenarios specified have been chosen less for their realism than for the amount of information that they yield about the effects of CHP/dh. For this reason, the scenarios investigated have all been specified so that each heat production process retains its market share relative to the other processes. In other words, no one of the conventional heating technologies is preferentially displaced by CHP/dh.

In practice, this is unlikely to be the case. It is beyond the scope of this present study to predict the extent to which different fuels will be displaced from the low grade heat market but it is clearly of great significance. The displacement of different fuels will depend upon a number of factors. For example, it is clearly likely that CHP/dh will be introduced mostly in densely populated areas of large conurbations. It is also likely that the fuel mix for heating such dwellings will have a lower proportion of oil than the national heating fuel mix. Even the particular cities involved will have an effect; Newcastle upon Tyne has a higher coal burn per capita than London. Apart from this effect, which might be termed 'geographical', the entry of a new technology, with considerable fuel inputs and knock-on effects, is likely to further change relative prices of fuels. While it has been argued (6.1) that the cross-elasticities between fuels are considerably less than might be supposed, it can be speculated that over the period that it takes for the activity of the CHP/dh process to build up to the levels discussed here, there will be significant changes in the conventional fuel mix.

As indicated above it would be foolish to speculate about these effects without considerable further study. The purpose of the present investigation is to establish the effects attributable to CHP/dh utilisation rather than prediction of the future!

6.2.4 CHP and HOB constraints

Eleven CHP and HOB technologies are described in the matrix A - B. Since they all share a principal production (waterborne heat for distribution), ten constraints are required to determine the inverse of the matrix. Each of the technologies has been investigated in turn by setting activity levels of the remaining ten to zero. The reason for this approach is to derive as much useful information as possible rather than an expression of a belief in the realisability (or desirability) of single technology CHP/dh programmes. A speculative district heating programme has also been investigated by specifying suitable constraints (see Appendix 5).

6.2.5 District heating penetration constraints

Two further constraints specifications are required. These are those required to determine the activity of CHP/dh and HOB/dh technologies relative to conventional technologies. This is done by specifying the activity levels of the heat distribution processes which are normalised so that at unit activity levels they are capable of supplying respectively the whole of the commercial and domestic low grade heat requirements of the UK. The value specified in the constraints part of the final demand vector is thus the penetration of district heating into each of the two heat markets.

6.3 SCENARIOS INVESTIGATED

To fulfil the aims of the pilot study, six main groups of scenarios were investigated. These are summarised in Table 6.1. The CHP and HOB technologies are specified in Appendix 5. The different technologies relate to different efficiencies, heat to power ratios and fuel inputs and are itemised in Table 6.1A.

Group 1 in Table 6.1 contains only one scenario; that representing 'the present day'. The equation $x = (A - B)^{-1}f$ should for this case yield a vector x whose elements x_j are ones for existing processes and zeros for non-existent processes when f is the 1977 final demand together with the appropriate constraint values. The full matrix A - B is particular to the scenario because it contains the constraints which define the scenario.

	North Sea gas available	North Sea gas replaced by Synthetic Natural gas
	Group 1: the present day (no CHP/dh)	Group 2: present day technology with no North Sea gas
10% penetration by dh into commercial and domestic low grade heat markets	Group 3: CHP/dh technologies 1 2 3 4 5 7 & 8 HOB/dh technologies 9 10 11 'speculative programme'	Group 4: CHP/dh technologies 1 2 3 4 5 7 & 8 HOB/dh technologies 9 10 11 'speculative programme'
30% penetration by dh into commercial and domestic low grade heat markets	Group 5: CHP/dh technologies 1 2 3 4 5 6 7 & 8 HOB/dh technologies 9 11 'speculative programme'	Group 6: CHP/dh technologies 1 2 3 4 5 6 7 & 8 HOB/dh technologies 9 11 'speculative programme'

Table 6.1 Scenario groups for pilot study

Technology	R	electrical efficiency	overall efficiency	fuel input	heat output (Mtherms)
1. Small diesel generator	4	17%	84%	4112 ktonnes	1187 Mtherms
2. Large coal fired steam turbine	2.4	25%	85%	4.8 Mtonnes	717 Mtherms
3. Small coal fired steam turbine	2.4	23.5%	80%	5.1 Mtonnes	717 Mtherms
4. High temperature heat output, coal fired steam turbine	1	28%	56%	4.3 Mtonnes	300 Mtherms
5. Nuclear powered steam turbine	2.4	-	-	-	717 Mtherms
6. Nuclear powered steam turbine	2.2	-	-	-	658 Mtherms
7. Small gas turbine for commercial/light industrial district heating	2	25%	75%	1196 Mtherms	897 Mtherms
8. Small gas turbine for domestic district heating	1.8	25%	70%	1196 Mtherms	897 Mtherms
9. Coal fired HOB's	-	-	80%	1.5 Mtonnes	299 Mtherms
10. Oil fired HOB's	-	-	85%	815 ktonnes	299 therms
11. Gas fired HOB's	-	-	82%	365 Mtherms	299 Mtherms

Table 6.1A CHP and HOB district heating technologies investigated (electricity output normalised to 8760 GWh).

Group 2 similarly contains only one scenario which is identical to the Group 1 scenario with the sole exception that the principal source of fuel gas is now SNG production since the level of North Sea gas is now constrained to an activity level of zero. The x vector generated will then reflect the changes in the activity levels attributable solely to the switch from North Sea gas to SNG.

Group 3 contains ten scenarios. The scenarios describe the effect of a 10% penetration of district heating into the heat market where the district heating is supplied by one of the eleven CHP or HOB technologies or by the 'speculative programme' described in Appendix 5. The x vector will show the changes in process activity levels attributable solely to the use of district heating to this extent.

Group 4 similarly contains ten scenarios as in Group 3 except that the Group 4 scenarios operate with the principal source of fuel gas being SNG production. The activity level of the North Sea oil production process is set at zero.

Groups 5 and 6 are similar to Groups 3 and 4 respectively except that district heating has a 30% share of the low grade heat market.

The scenarios outlined above have deliberately been kept very simple. This is in order that the basis for comparison for process activity levels is readily accessible and appreciated; in all cases it is the 1977 state of technology. The effects of each subsequent assumption can be individually assessed.

6.4 RESULTS AND CONCLUSIONS

Since the pilot study was very much a 'learn-as-you-go' exercise, results and conclusions are presented together. The extent to which the aims of the pilot study were achieved is also discussed.

6.4.1 Inversion and unnatural constraints

The construction and inversion of the matrix A - B for all the specified scenarios showed that the matrix was not only non-singlular but that it was sufficiently well conditioned that the matrix of residues contained no elements greater than 1×10^{-7} (see section 4.7.4.2 of Chapter 4). This fulfilled the first aim of the pilot study.

One 'rogue element' was discovered. This was a small entry describing the transport input to coal production. The output from the coal industry was found to be fixed at its 1977 level. By checking the elements of the matrix $A(A - B)^{-1}$ for a number of constraint sets, it was discovered that it was this element which had the effect of artificially distorting the behaviour of the coal industry. This occurred because transportation is itself constrained by its interaction with the 'other goods and services' sector. The culprit element was set to zero. The loss of accuracy is justified when the marginal transport cost of additional coal production would, in the real world, have such a negligible effect upon the output of the transport sector. Coal production at 1977 levels of output requires only 2% of the total output of the transport sector. Further exploration of the matrix formulation revealed no other non-credible effects arising from individual elements.

6.4.2 Calibration

This has already been described in section 5.5 of Chapter 5. As a consequence of this procedure a steel importing sector was introduced in the full scale study.

6.4.3 Effects of depletion of North Sea gas

The calculated primary effect of depletion of North Sea gas, all other things being equal, is that the principal source of fuel gas becomes the synthesis of SNG, using coal as an input.

The effects of this process substitution can be tracked through the remainder of the system. The synthesis of adequate supplies of gas to replace the supply from the North Sea requires 95 million tonnes of coal which, if it is all supplied domestically, requires an increase of 78% in the production from mines. If North Sea oil stocks too are depleted, then an increase of 53% in imported oil is implied although the net quantity of crude oil required remains the same. The additional activity in the coal mines requires that additional electricity be supplied to the mines. Under the assumptions about electricity production used in the pilot study, an additional activity of 2.5% is required of middle order (ie coal fired) power stations, corresponding to an overall increase of 1.8% in the activity level of the electricity industry, as measured by the activity of the 'electricity transmission' process. An interesting 'second order effect' of the depletion of North Sea gas stocks is a 5% increase in refined fuel oil imports to replace the 704 thousand tonnes of light distillate produced as a by-product of North Sea gas extraction.

It is interesting to note that the coal intensity of low grade heat in the Group 2 scenario is 10.69 thousand tonnes per Megatherm compared with only 5.77 thousand tonnes per Megatherm in the North Sea gas, group 1 scenario. Furthermore, shifts in the relative shares of coal and gas in the domestic heat market towards gas 'cost' only 0.4941 thousand tonnes per Mtherm in the SNG scenario compared with 6.464 thousand tonnes per Mtherm in the North Sea gas scenario. This is because in the former case, the greater part of the 'cost' is offset by the reduced quantity of coal needed to produce the gas. This result certainly reinforces the notion that there are likely to be much stronger economic pressures reducing gas's market share relative to coal in the SNG scenario scenario case.

A 'first off' assessment of this scenario suggests that the 'all other things being equal' feature of this scenario is quite unreasonable since it is difficult to visualise an adequate increase in the activity of coal mines within the time scale commonly assumed for the depletion of North Sea gas, even if it were possible to build adequate SNG capacity. These effects are summarised in Tables 6.2 and 6.3.

6.4.4 Effects of using district heating

6.4.4.1 10% penetration: no SNG

In the group 3 set of scenarios, the case is considered where 10% of both commercial and domestic low grade heat is supplied by district heating. The outcome of this set of calculations is set out below.

In all cases coal requirements are reduced. Coke requirements are reduced to 96.8% of their 1977 levels. In all but one case each, fuel gas and refined oil import requirements are reduced as are total electricity requirements.

Reduction in gas requirements occurs for all technologies specified with the exception of CHP/dh technology 7 and CHP/dh technology 8 which are both based on gas turbines (being 'commercial gas CHP' and 'industrial total energy' respectively). However, interestingly, even gas fired HOBs have the potential to reduce total gas requirements slightly although gas could be said to be increasing its market share. This is because of the greater efficiency with which gas can be burned in large boilers.

Table 6.2 Total requirements of Groups 1 and 2 scenarios

	Group 1 scenario	Group 2 scenario	
fuel gas	16853	16853	Mtherms
coal	124.5	221.6	million tonnes
coke	13.6	13.6	million tonnes
crude oil	108237	108273	th.tonnes
refined fuel oil	64317	64317	th.tonnes
other refined oil	33338	33338	th.tonnes
electricity generated	242993	247358	GWh
electricity sold	220904	224872	GWh
petrochemicals	1	1	1977 prodn.
iron and steel	1	1	1977 prodn.
other goods and services	1	1	1977 prodn.
transport	1	1	1977 prodn.
commercial low grade heat	3267	3267	Mtherms
domestic low grade heat	6637	6637	Mtherms
heat for distribution	0	0	Mtherms

Table 6.3 Activity level of Groups 1 and 2 scenarios

North Sea gas production	1	0
SNG production	0	95.1
coal mines	1	1.78
coke ovens	1	1
North Sea oil production	1	0
crude oil imports	1	1.53
oil refineries	1	1
imports of refined fuel oil	1	1.05
gas power stations	1	1
coal fired power stations	1	1.02
oil fired power stations	1	1
nuclear power stations	1	1
electricity transmission	1	1.02
petrochemical industry	1	1
iron and steel production	1	1
other manufacturing and services	1	1
transport	1	1
commercial heating	1	1
domestic heating	1	1

The reduction in coke requirements is independent of the particular type of CHP/dh technology used, since coke is not an input to either a CHP/dh technology nor to electricity generation plant, its reduced level of demand arises purely as an effect of reduced market share.

Similarly, the requirement for imported refined fuel oil is independent of technology except where oil is the direct input to the CHP/dh technology. This occurs because the activity level of the oil fired power stations is constrained to its 1977 level and is thus unaffected by changes in electricity demand. The 'background' reduction in refined fuel oil imports is 7% although in the case of oil fired HOBs the reduction is only 5% (again increased efficiency more than off-sets the increase in market share). Only in the case of diesel CHP/dh (CHP/dh technology 1) is there actually an increase in the requirement for fuel oil imports although here it is a dramatic 19%, suggesting that balance of payments implications require careful consideration before even a modest CHP programme based on diesel technology is implemented.

The quantity of electricity generated by the CHP/dh technologies depends upon the heat to power ratio. 'Market share' effects can be determined by examining the HOB cases where it is found that the activity of the 'middle order', ie coal-fired, plant is reduced to 96% of its previous level and total electricity requirements to 97% of their previous level. The use of CHP technologies all result in a reduction of between 20% (CHP/dh technology 4; coal fired plant with heat:power ratio of 1) and 7% (speculative programme) in the activity of the middle order plant. The overall activity of the public electricity supply is reduced still further in the case of CHP/dh technologies 7 and 8 since these replace public generation with local generation, supplying direct to commercial/industrial consumers, thus reducing the activity level of the transmission process.

The activity level of the coal industry is influenced by several factors; the extent to which coal-based electricity production is displaced, the efficiency of the coal-based CHP plant and the displacement of coal and coke from the low grade heat markets. The activity of the coal mines then shows much more variation between individual technologies; an 8% reduction in the case of nuclear powered CHP/dh and only a 3% reduction in the case of a less efficient coal based CHP/dh technology.

The general conclusion that can be drawn from this exercise is that the capture of a part of the market by a particular fuel via CHP/dh or HOB/dh does not in general lead to an increase in the activity of that particular fuel production. The enhanced efficiency of energy conversion in CHP and HOB plant does in general lead to reduction in the consumption of all fuels including that supplying the CHP plant. This is true of all CHP/dh technologies except diesel based CHP. This runs counter to the declared plans of the National Union of Mineworkers to promote coal-based CHP as a means of enchancing the activity of the coal industry.

Activity level data is summarised in Table 6.4.

6.4.4.2 30% penetration : no SNG

The trends already evident in the group 3 scenarios are shown to a greater extent in group 4, where district heating has 30% of the low grade heat market. Indeed in this simple pilot study, there is a linear relationship between the market penetration and the activity levels where these change.

The effects of a 30% penetration of CHP/dh into low grade heat markets upon the fuel processes and the total fuel requirements are shown in

CHP/dh tech'y / process	1	2	3	4	5	7 & 8	9	10	11	programme
North Sea gas production	.959	.959	.959	.959	.959	1.059	.959	.959	.967	.959
coal mining	.934	.970	.973	.967	.915	.914	.965	.961	.961	.961
coke ovens	.968	.968	.968	.968	.968	.968	.968	.968	.968	.968
refined fuel oil imports	1.193	.930	.930	.930	.930	.925	.930	.945	.930	.930
coal fired electricity generation	.922	.895	.895	.799	.894	.891	.964	.964	.964	.934
electricity transmission	.973	.974	.974	.974	.974	.922	.974	.974	.974	.974
CHP electricity capacity (GW)	.834	1.381	1.381	3.301	1.381	1.213 1.410				1.315

Table 6.4 Process activity levels (1977 = 1); 10% penetration by CHP/dh; no SNG

tables 6.5 and 6.6 respectively. While the effect of technology upon total requirements for refined fuel oil is shown to be of limited significance, the effect upon imports, as the marginal source of refined fuel oil is shown (in Table 6.5) to be of rather greater significance. The effects upon the electricity industry and upon electricity requirements are shown in rows 5 and 6 of Table 6.5 where the domestic effect of the use of CHP plant with low heat:power ratios can be seen (technology 4). It can also be shown that at a hypothetical 50% penetration of CHP/dh, all electricity previously generated by coal plant is displaced by electricity produced by CHP plant.

Energy supply schedules for CHP/dh technologies 1 to 11 are shown in figures 6.1A and 6.1B and 6.1C.

In addition to the scenarios specified in table 6.1 it was also found useful to determine the effects of implementing a conservation programme which would save 10% and 30% respectively of low grade heat consumption. These are shown in figure 6.2 which may usefully be compared with figure 6.1. (See also table 6.7 which may be compared with tables 6.4 and 6.5.) In fact, this exercise, using the very simple model of the pilot study, reveals no more than can be deduced from judicious study of tables 6.4 and 6.5.

6.4.4.3 10% penetration: no North Sea gas

The study shows that with the simple model of the electricity industry used in the pilot study, the effects of the use of CHP/dh and SNG synthesis are additive. In other words, the trends revealed for the group 4 scenarios reflect those of groups 3 and 5 with the addition of the effects of SNG synthesis to replace North Sea gas extraction. Process activity levels for the group 4 scenarios are recorded in table 6.8 in which the activity levels for the group 2 scenario are recorded for comparison.

CHP/dh tech'y / process	1	2	3	4	5	7 & 8	9	10	11	programme
North Sea gas production	.877	.877	.877	.877	.877	1.177	.877	.759	.901	.892
coal mining	.801	.910	.920	.902	.747	.743	.895	.761	.883	.881
coke ovens	.903	.903	.903	.903	.903	.903	.903	.768	.903	.903
refined fuel oil imports	1.579	.791	.791	.791	.791	.775	.791	.745	.789	.810
coal fired electricity generation	.765	.686	.686	.397	.681	.675	.893	.764	.893	.826
electricity transmission	.927	.923	.923	.923	.919	.766	.923	.774	.923	.923
CHP electricity capacity (GW)	2.503	4.144	4.144	9.904	4.144	1.64 2.34				1.327

Table 6.5 Process activity levels (1977 = 1); 30% penetration by CHP/dh; no SNG

CHP/dh tech'y / process	1	2	3	4	5	7 & 8	9	11	programme
gas (Mtherm)	14916	14916	14916	14916	14916	220062	14916	15319	15148
coal (Mtonne)	99.7	113.3	114.6	112.3	93.0	92.5	111.5	92.5	109.8
coke (Mtonne)	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3
refined fuel oil (ktonnes)	71792	61500	61500	61500	61500	64317	65383	61500	61759
electricity (TWh)	33338	33338	33338	33338	33338	33338	33338	33338	33338

Table 6.6 Energy requirements: 30% penetration by CHP/dh; no SNG

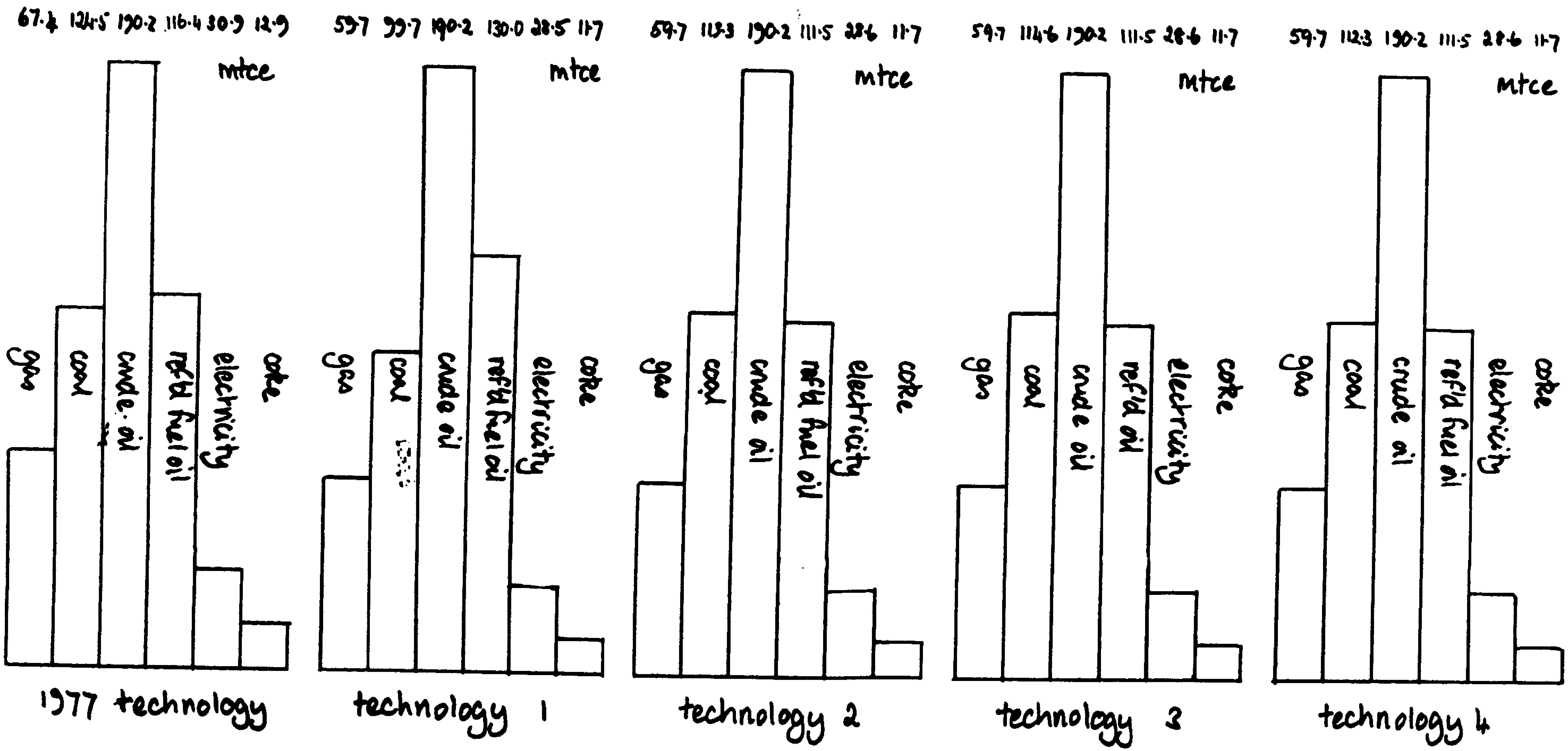

Figure 6.1A Energy requirements of district heating technologies:
30% penetration of heat market : no SNG

Scale : 1" ≡ 50 mtce

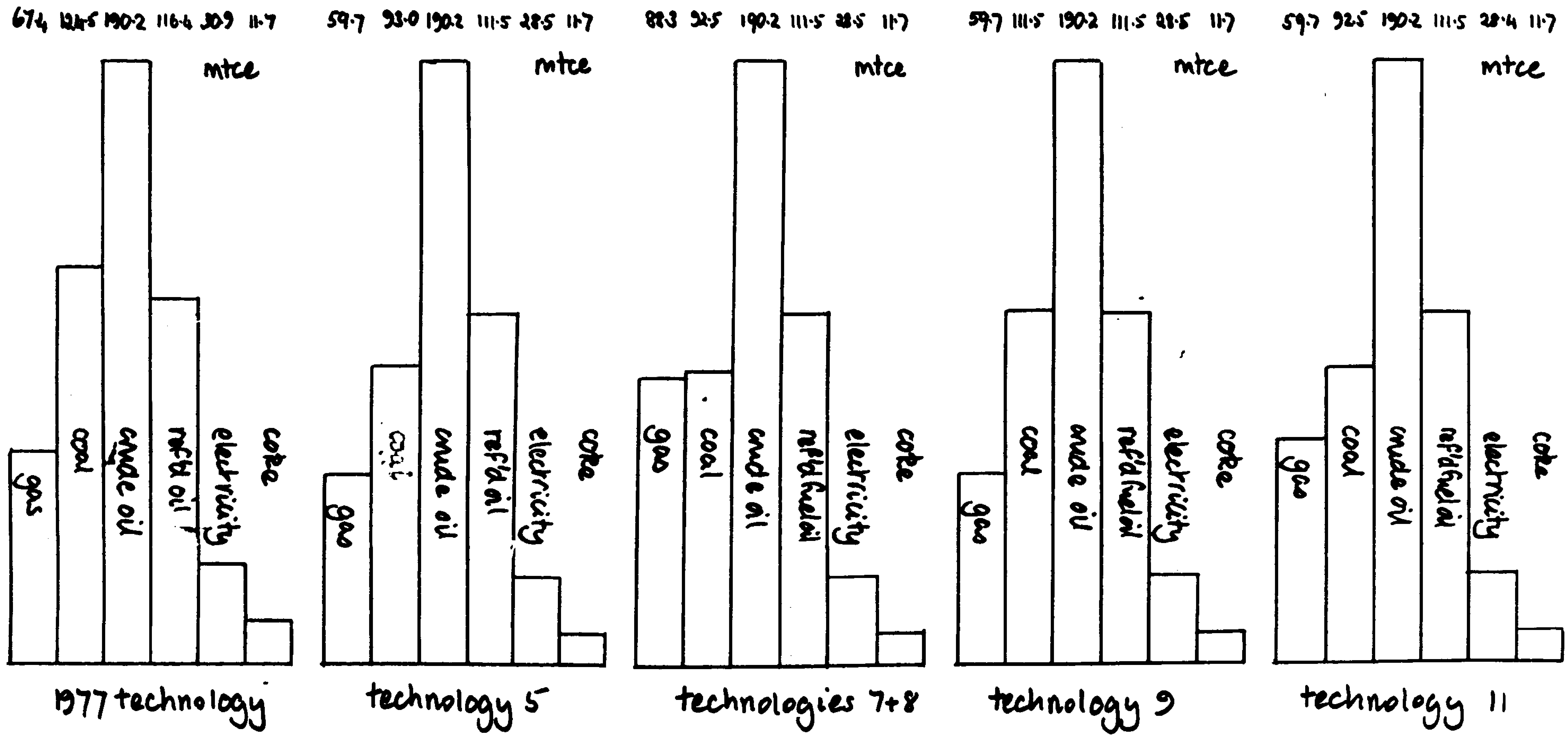

Figure 6.1B Energy requirements of district heating technologies :
30% penetration of heat market : no SNG

Scale : 1" ≡ 50 mtce

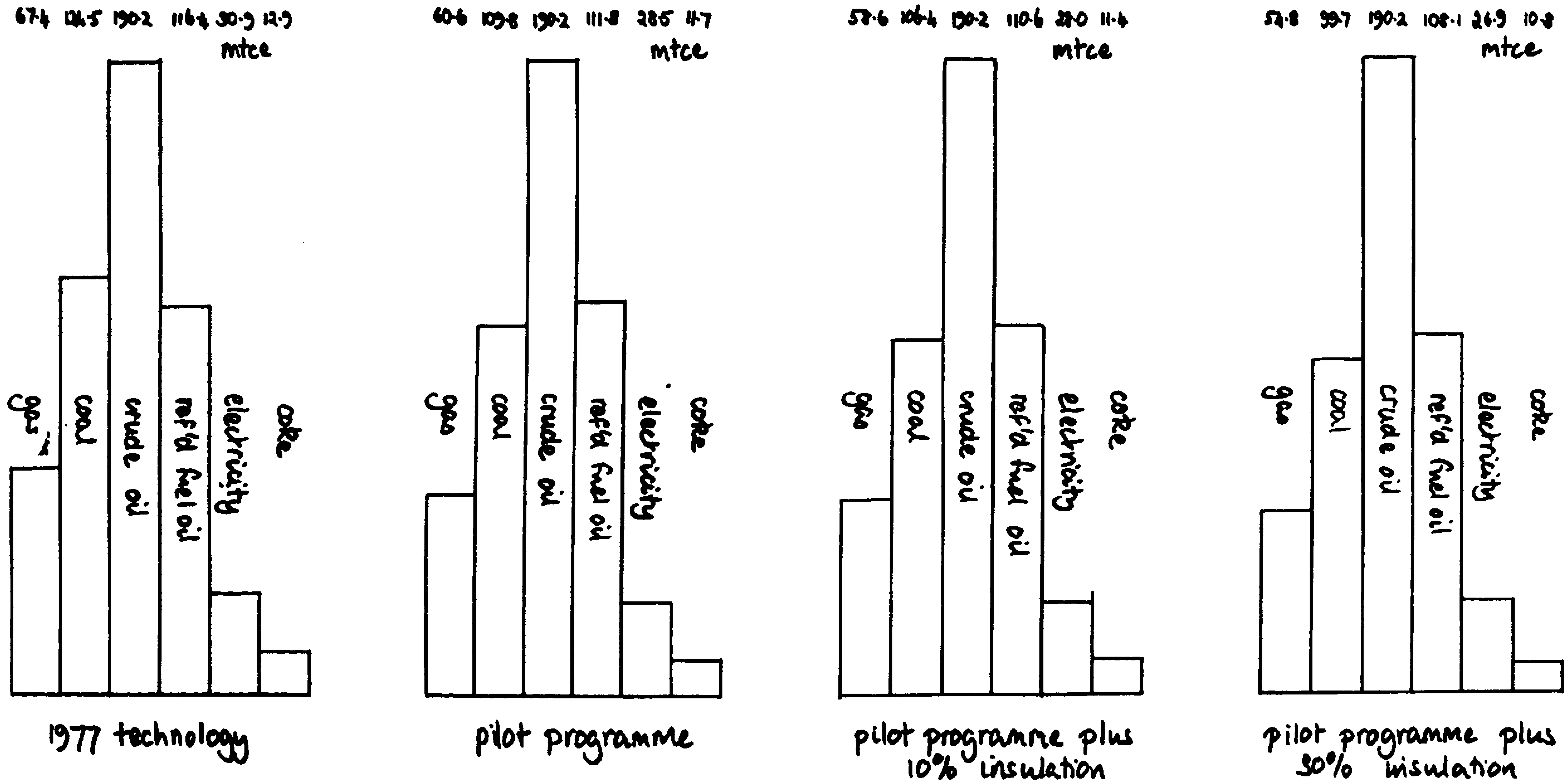

Figure 6.1C Energy requirements of pilot programme : 30% penetration of heat market : no SNG

Scale : 1" ≡ 50 mtce

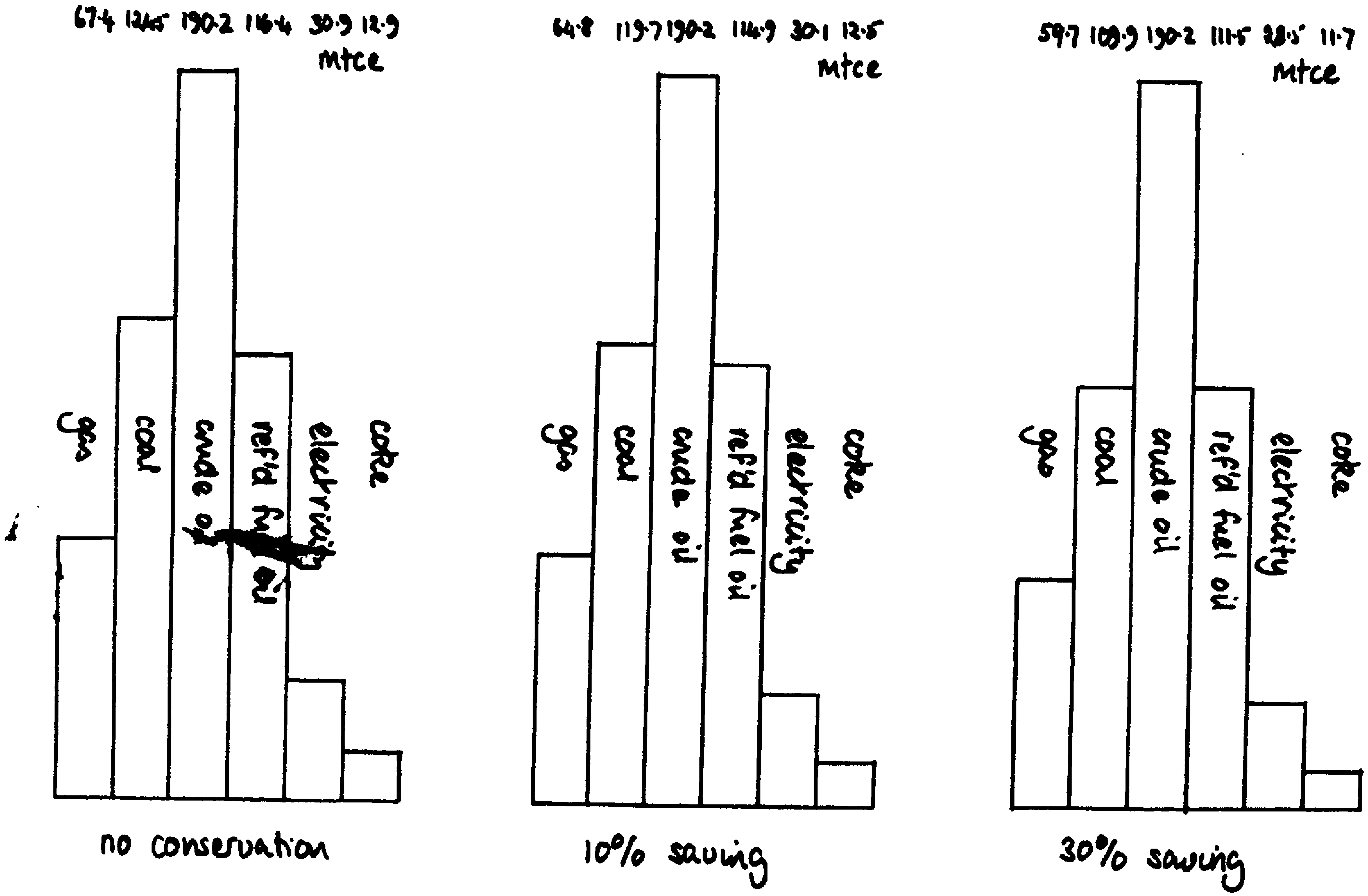

Figure 6.2 Effect of conservation on energy requirements :

Scale : 1" ≡ 50 mtce

extent of conservation / process	10%	30%
North Sea gas production	.959	.877
coal mining	.961	.883
coke ovens	.968	.903
refined fuel oil imports	.930	.791
coal fired electricity generation	.964	.893
electricity transmission	.974	.923

Table 6.7 Effect of low grade heat conservation upon process activity level

process \ CHP/dh tech'y	Group 2	1	2	3	4	5	7 & 8	9	11	programme
SNG production	95.071	91.179	91.179	91.179	91.179	91.179	100.674	91.179	91.924	91.205
coal mining	1.780	1.681	1.718	1.721	1.715	1.633	1.723	1.713	1.715	1.709
coke ovens	1.000	.968	.968	.968	.968	.968	.968	.968	.968	.978
refined fuel oil imports	1.054	1.245	.982	.982	.982	.982	1.245	.982	.982	.982
coal fired electricity generation	1.025	.945	.919	.919	.823	.918	.891	.988	.988	.928
electricity transmission	1.018	.991	.992	.992	.992	.990	.941	.992	.992	.991
CHP electricity capacity (GW)	0	.834	1.381	1.381	3.301	1.381	.547 .743			

Table 6.8 Process activity levels (1977 = 1) : 10% penetration of CHP/dh ; no North Sea gas

6.4.4.4 30% penetration: no North Sea gas

The resultant activity levels for the group 6 scenarios are recorded in table 6.9 with the activity levels for 'conservation only' being recorded for comparison in table 6.10. Fuel requirements for those scenarios are recorded in table 6.11 and shown graphically in figures 6.3A, 6.3B and 6.3C. The effects of conservation are shown in figure 6.4.

6.4.5 Summary

As previously speculated (see Appendix 2), the indications of the pilot study are that the implications of CHP/dh involve interactions which have considerable bearing on all the fuel industries, not only in displacement from low grade heat markets but also, most particularly, in process substitution for electricity generation with corresponding knock-on effects to other fuels. There are also strong indications that because of efficiency improvement, coal which is used as inputs to CHP/dh plant does not in fact increase its total market share. CHP/dh technologies with low heat to power ratios would displace quite substantial parts of the conventional power station stock.

This indicates that the considerable effort required to develop the full scale model, capable of dealing in part with particular effects upon the electricity industry is not misdirected.

6.5 SUMMARY OF PILOT STUDY

Although the pilot project required considerable time and effort and although the results obtained can only be taken as indicative, the study was found to be very worthwhile. This is not only because it is possible to speculate about the difficulties of disentangling problems with very much larger matrices but also because it was possible to proceed quite efficiently with the matrix description of the electricity industry, with confidence that the description of the remainder of the

CHP/dh tech'y / process	Group 2	1	2	3	4	5	7 & 8	9	11	programme
SNG production	95.071	83.396	83.396	83.396	83.396	83.396	111.880	83.396	85.630	84.822
coal mining	1.780	1.485	1.594	1.604	1.586	1.431	1.608	1.579	1.585	1.577
coke ovens	1.000	.903	.903	.903	.903	.903	.903	.903	.903	.903
refined fuel oil imports	1.054	1.627	.838	.838	.838	.838	1.627	.838	.838	.858
coal fired electrcity generation	1.025	.787	.708	.708	.419	.703	.622	.915	.915	.848
electricity transmission	1.018	.936	.939	.939	.939	.935	.786	.939	.939	.939
CHP electricity capacity (GW)	0	2.503	4.144	4.144	9.904	4.144	1.64 2.23			

Table 6.9 Process activity levels (1977 = 1): 30% penetration by CHP/dh; no North Sea gas

extent of conservation / process	1977	10%	30%
SNG production	95.071	91.178	83.394
coal mining	1.780	1.709	1.567
coke ovens	1.0	0.968	0.903
refined fuel oil imports	1.054	0.982	0.838
coal fired electricity generation	1.025	0.988	0.914
electricity transmission	1.018	0.991	0.938

Table 6.10 Effect of low grade heat conservation upon process activity level

CHP/dh tech'y / process	1	2	3	4	5	7 & 8	9	11	programme
gas (Mth)	14916	14916	14916	14916	14916	19545	14916	15280	15148
coal (Mtonnes)	184.9	198.4	199.7	197.5	178.2	200.2	196.6	197.4	196.4
coke (Mtonnes)	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3
refined fuel oil (ktonnes)	71792	61500	61500	61500	61500	61500	61500	61500	61759
electricity (TWh)	227559	228171	228228	228126	227257	176811	228088	228122	228071

Table 6.11 Energy requirements: 30% penetration by CHP/dh: no North Sea gas

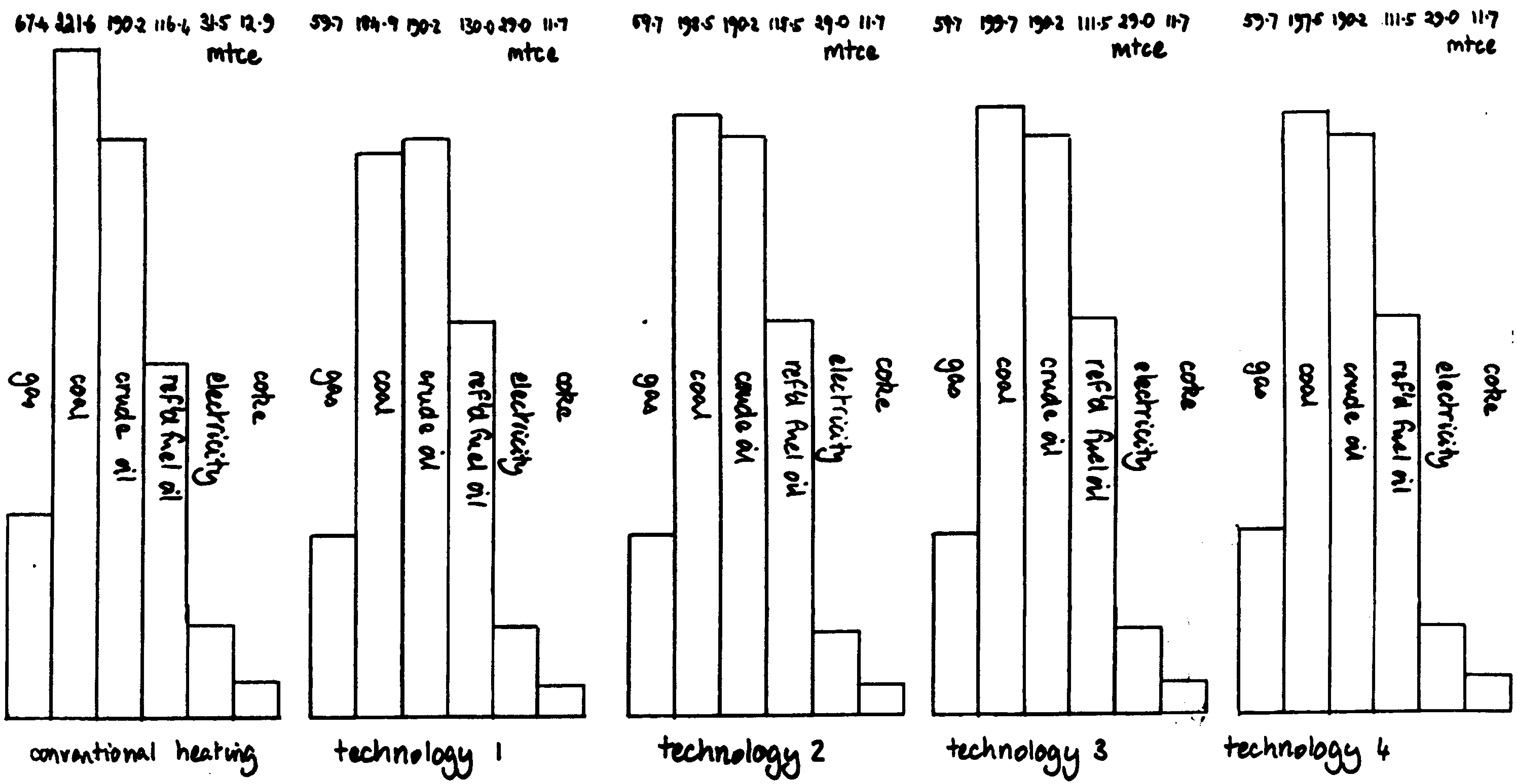

Figure 6.3A Energy requirements of district heating technologies :
30% penetration of heat market : no North Sea gas

Scale : 1" = 50 mtce

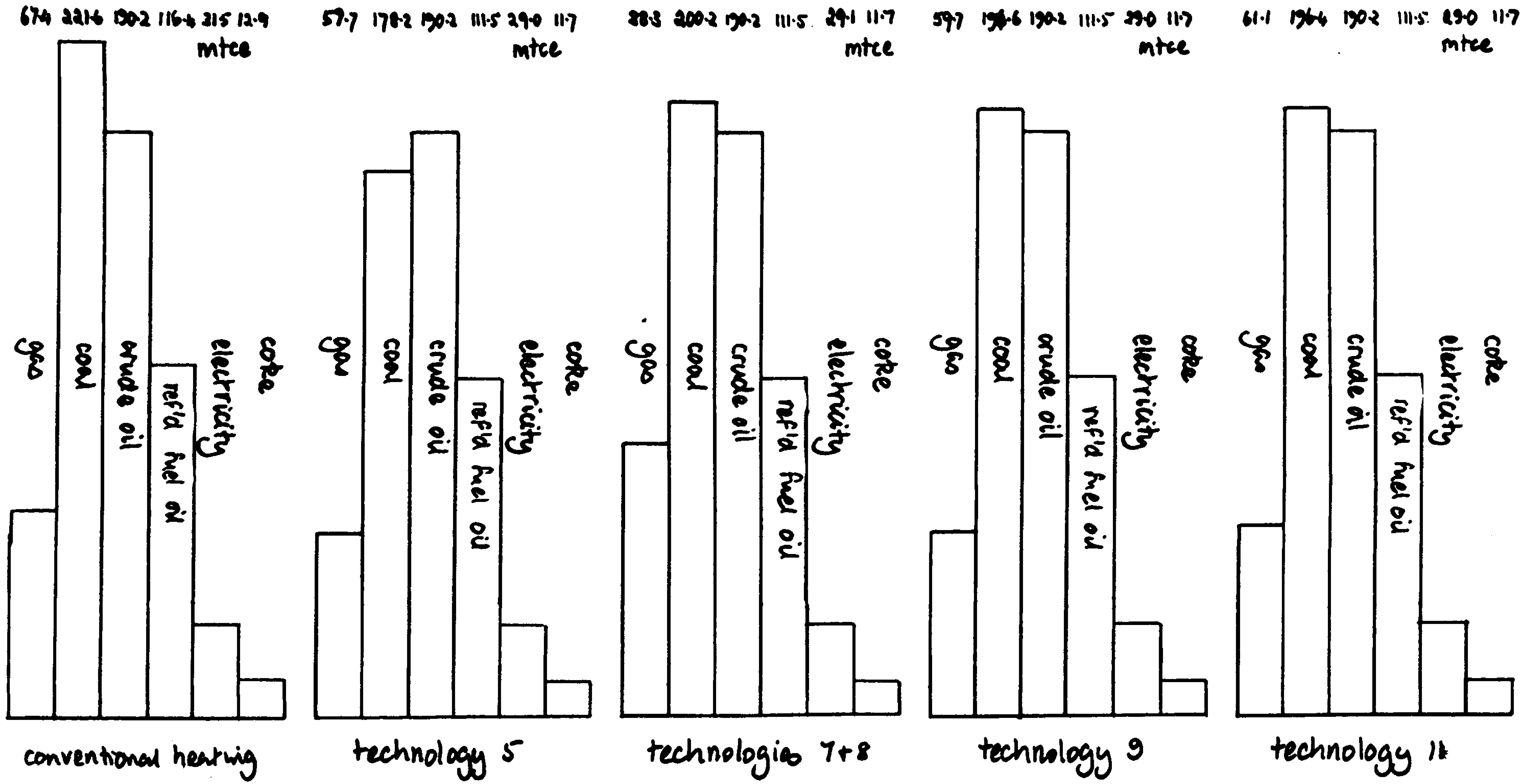

Figure 6.3B Energy requirements of district heating technologies :
30% penetration of heat market : no North Sea gas

Scale : 1" ≡ 50 mtce

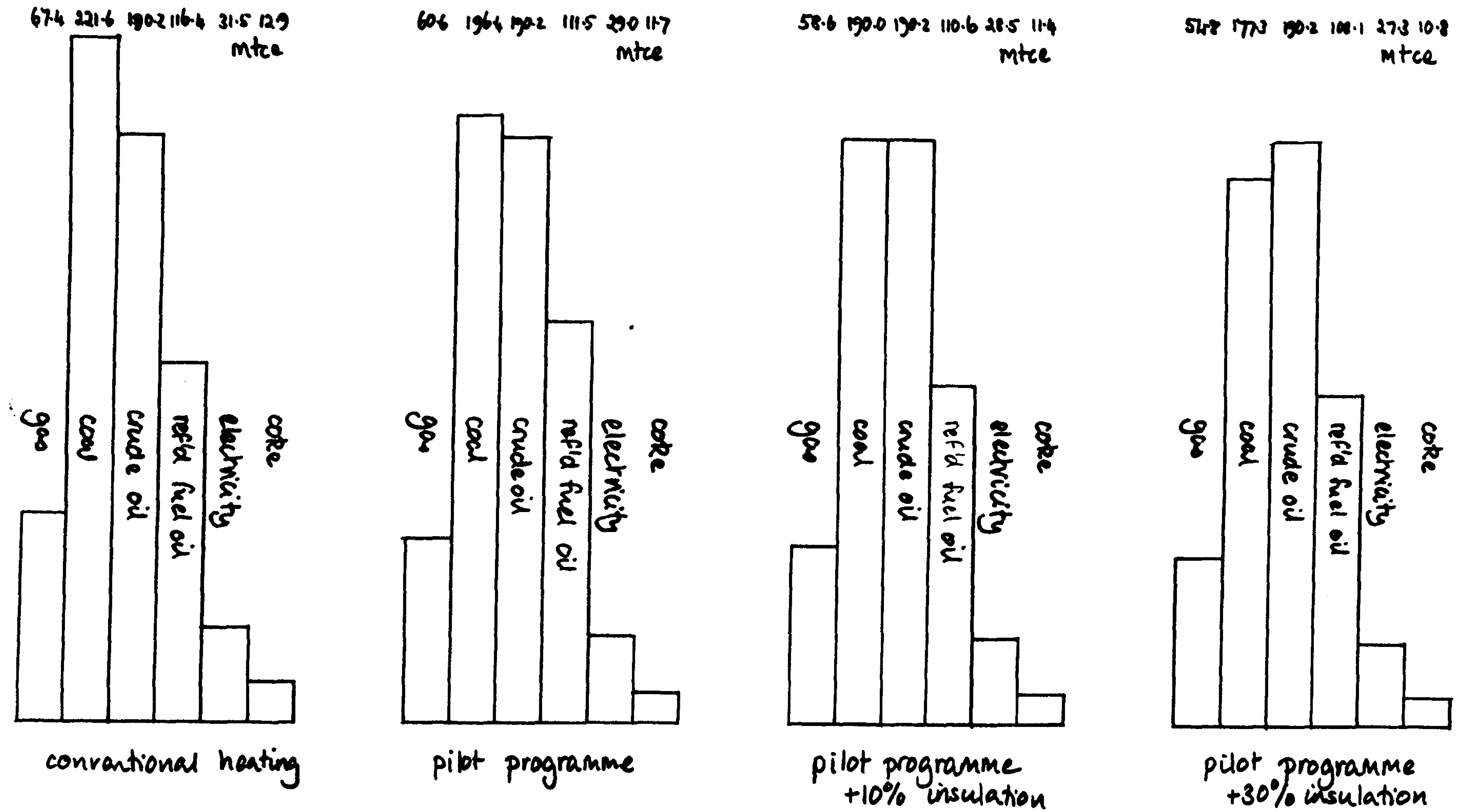

Figure 6.3C Energy requirements of pilot programme : 30% penetration of heat market : no North Sea gas

Scale : 1" ≡ 50 mtce

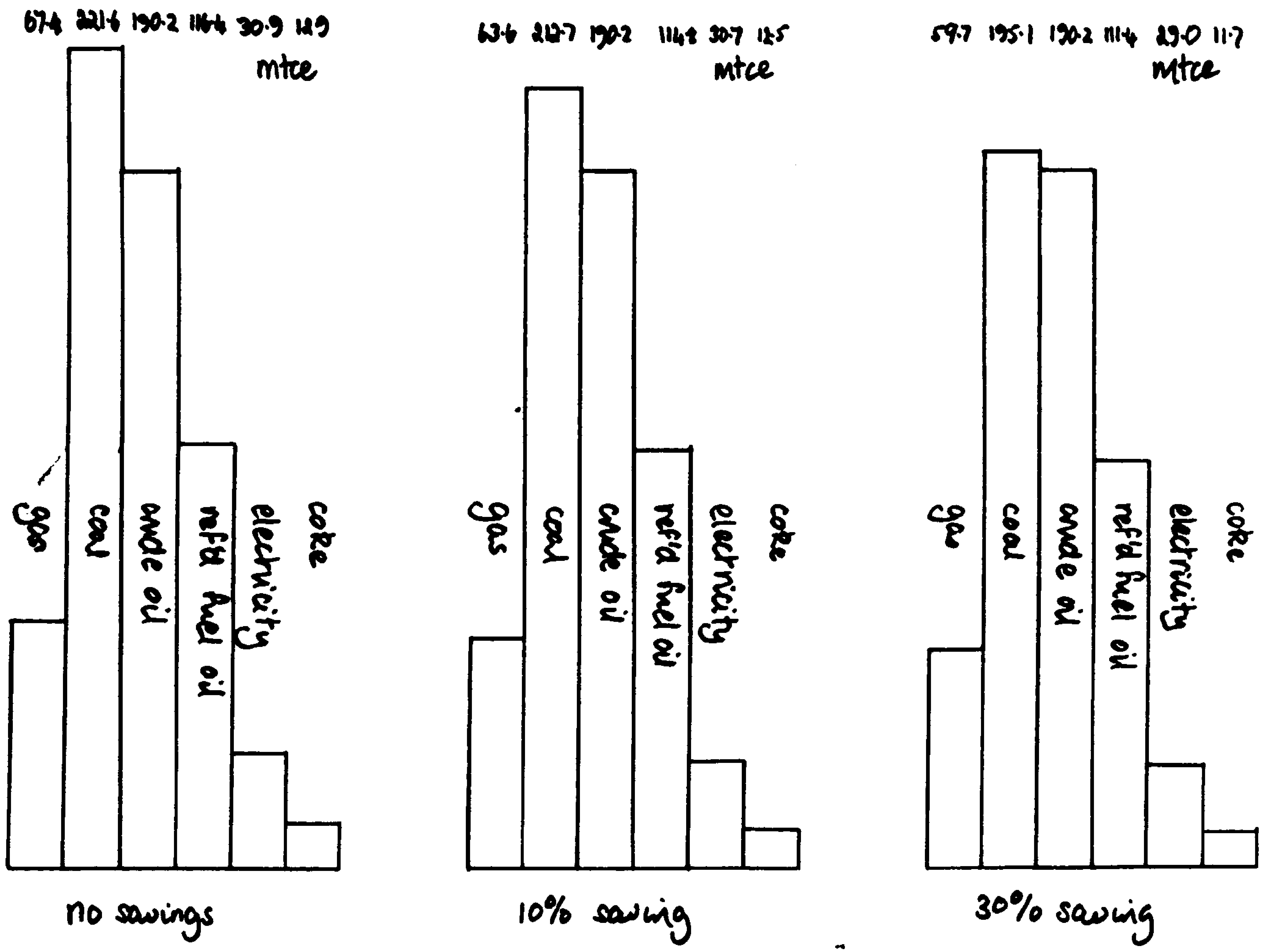

Figure 6.4 Effect of low grade heat conservation on energy requirements : no North Sea gas

Scale : 1" ≡ 50 mtce

system had been 'passed fit' with only minor modifications and improvements. In addition, the results of the pilot study vindicated the idea that the electricity industry and its interactions with both CHP/dh and other energy technologies is of fundamental importance in understanding the likely implications of introducing a technology like CHP/dh.

7 MODELLING ELECTRICITY GENERATION

7.1 NON-LINEARITY

Electricity generation is treated separately in this study because of its non-linear characteristics. The model described in Chapter 6 requires that for all inputs and outputs of process j, $\partial b_{kj}/\partial a_{ij}$ and $\partial a_{kj}/\partial a_{ij}$ are constant and independant of the magnitude of a_{ij}. Most processes within the industrial system can be said to approximate these relationships, at least at the margin, although it is commonly observed that $\partial b_{kj}/\partial a_{ij}$ decreases slightly as a_{ij} increases. In other words, the production of a_{ij} becomes more efficient as the production of a_{ij} increases. This may be as a result of 'economies of scale' or, in the case of maturing technologies, as a result of 'learning'.

Electricity generation taken over the whole industry does not conform even remotely to this description. Indeed, with a given stock of plant the instantaneous average efficiency of generation falls as the rate of output increases.

In fact, electricity generation is non-linear in two senses. The quality and quantity of input per unit output depending not only upon the quantity of output but also upon the way in which the rate of output varies through the year. To make this point quite clear reference can be made to the diagrams of figure 7.1 which shows electricity production over a period of time t. Simple non linearity would lead us to the conclusion that inputs per unit output for (b) would be different to those of (a) since total production during the time period is increased. However, for the particular case of the electricity industry, the inputs per unit output over the time period t for the case of (c) will be different from (b) even though they have the same net output during the time period. To summarise; for a simple linear process

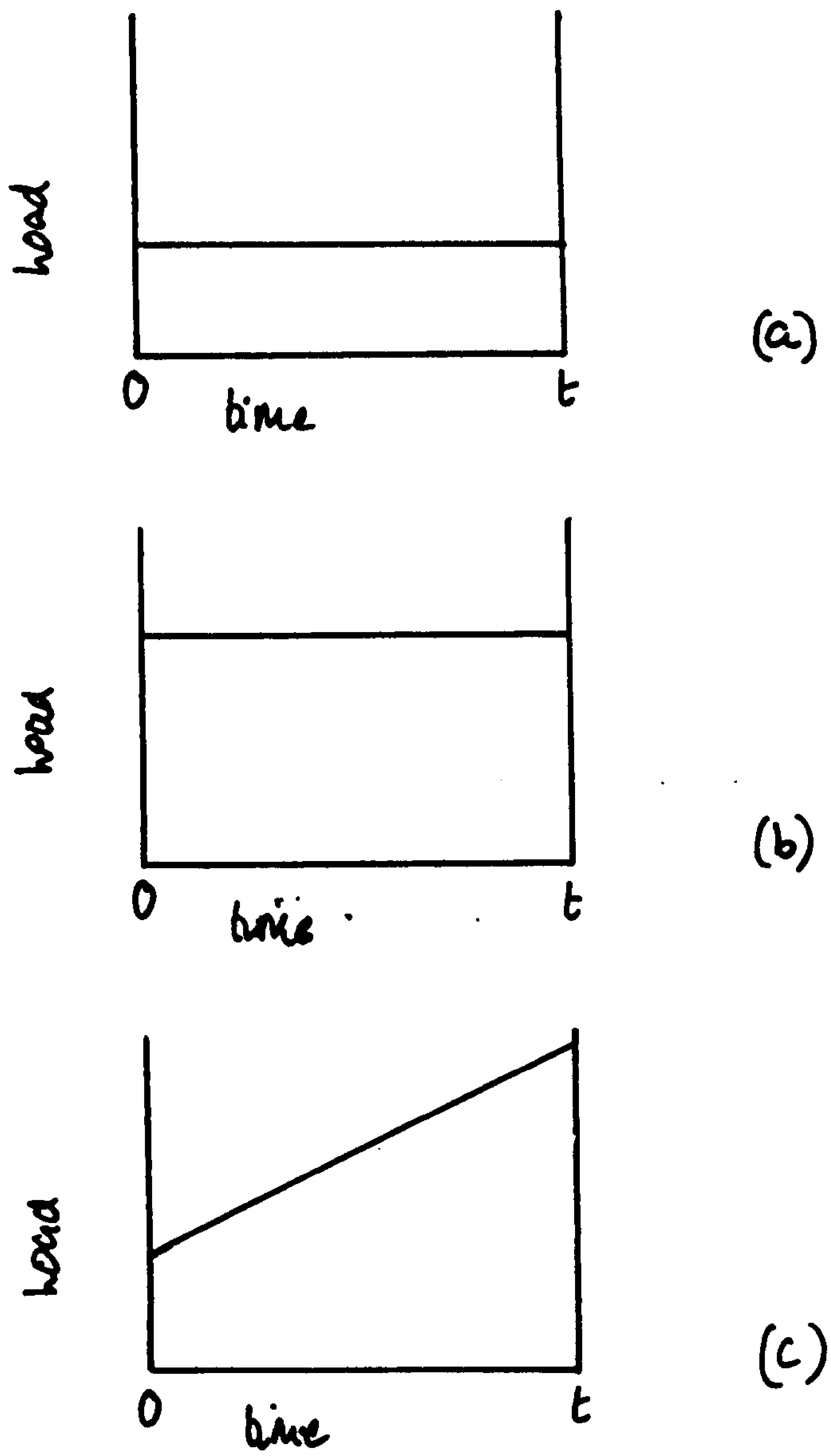

Figure 7.1 Electricity demand over time period t

$$\partial b_{kj}/\partial a_{ij} = \text{constant} \tag{7.1}$$

for a simple non-linear process

$$\partial b_{kj}/\partial a_{ij} = f(a_{ij}) \tag{7.2}$$

for electricity generation

$$(\partial b_{kj}/\partial a_{ij})_t = \text{function } (da_{ij}/dt)_t \tag{7.3}$$

In other words electricity generation, taken on a national scale is a dynamic process whose input-output ratios depend upon the instantaneous rate of generation. It is for this reason that the generation of electricity in the UK cannot be incorporated directly into the model described in Chapters 4 and 6.

7.1.1 The merit order

The CEGB supplies electricity in England and Wales at a rate which varies between an annual minimum of approximately 10GW and an annual maximum of approximately 50GW. The load upon the system varies very rapidly and exhibits various levels of predictability.

In order to meet this demand, the CEGB possesses some 57GW (1977 data (7.1)) of generating capacity. This capacity is made up of nuclear, coal-fired and oil fired steam plant together with small quantities of gas and diesel turbine and hydroelectric plant. These plant have different efficiencies and operating costs and the capital charges per Gigawatt of the plant also varies with the type and age of plant.

Costs can be attributed to each Gigawatt of plant in the system. If the capital charges for a particular unit of capacity in the system are K £/GW and the running costs of using that unit of capacity (mainly attributable to fuel costs) are F £/GWh, then the cost of each unit of electricity generated will be

$$\text{cost per GWh} = \frac{K}{\lambda} + F \tag{7.4}$$

where λ is the annual average load factor of the unit of capacity in question.

The cheapest mix of generation technologies can be determined by reference to a diagram of the type illustrated in figure 7.2 in which the cost per GWh for four types of plant, a, b, c and d, are plotted. This shows that for load factors between 1 and λ_{ab}, the high load factors, plant type a is the most cost effective. At low load factors, plant d is the most cost effective. Thus it is that high capital cost low running cost plant such as nuclear plant operates with high load factors while low capital cost high running cost plant such as gas turbines operates at times of peak load and hence with low load factors. Plant is selected for the system on the basis of the anticipated requirement for capacity with specific load factors.

On a day to day basis, generating plant is ranked in 'merit order' so that those with the lowest running cost are used first. It is possible to do this only because all points of consumption are connected to all points of production through the National Grid. But it is only necessary to operate in this way because electricity storage is prohibitively costly. If it were not then the generating system could operate at high load factors and electricity could be stored during periods of low demand for later periods of high demand.

While a simple model of the merit order is adequate for most purposes, in fact the day to day running of the electricity system is rather more complex than this since it may be appropriate at any time to bring in gas turbines or hydroelectric plant out of sequence where the anticipated duration of a forthcoming demand peak is short and where spinning reserve (hot turbines spinning against no load) is inadequate, since the run-up time for gas turbines is very short.

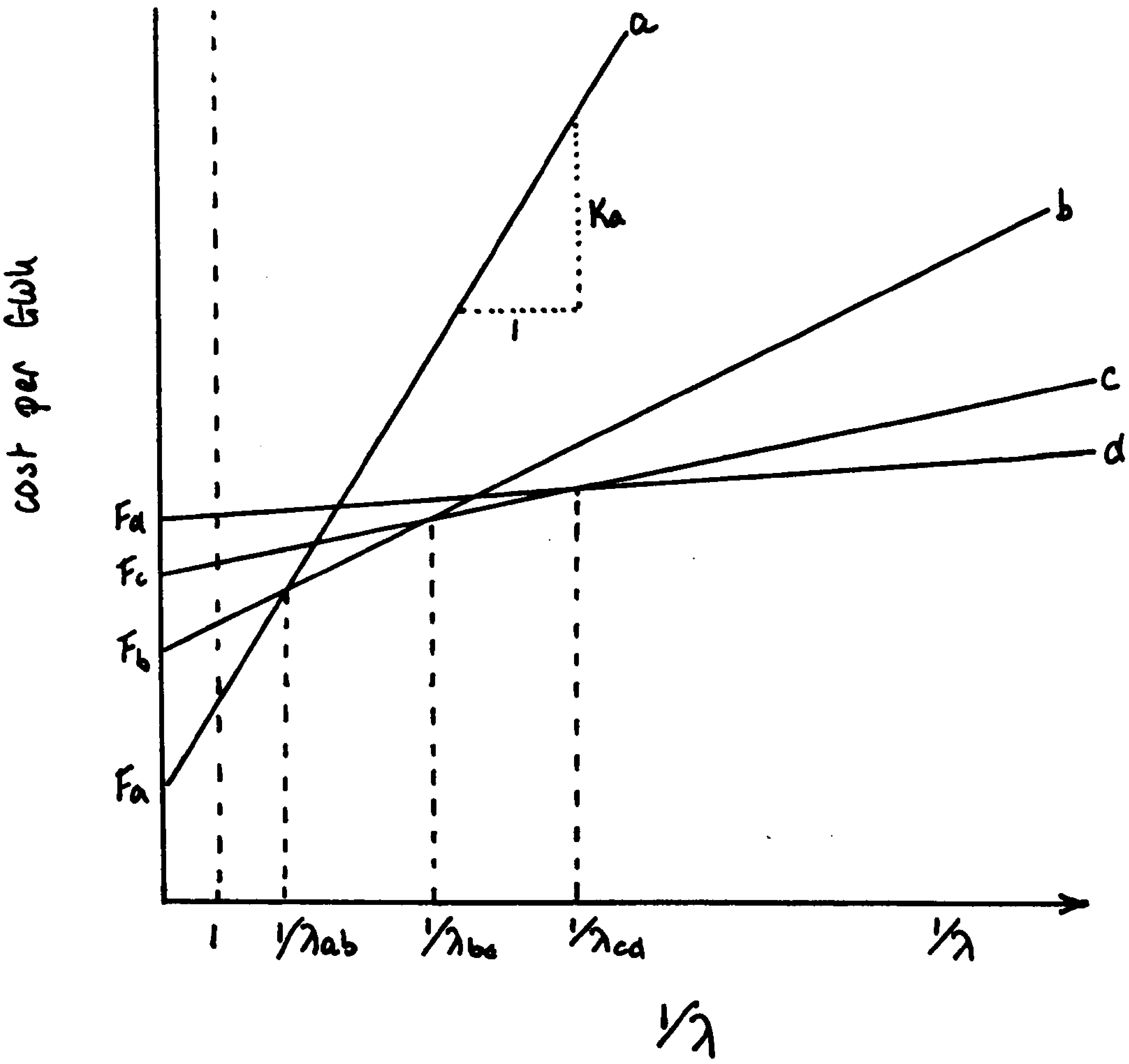

Figure 7.2 Unit cost as a function of plant load factor

The consequences of this for the modelling of the electricity system are that at periods of low demand, the inputs required to produce 1 GWh of electricity may be only nuclear heat, while at periods of moderate demand, the inputs might include coal, nuclear heat and oil, while the inputs per unit output at periods of high demand would include quantities of nuclear heat, coal, oil and gas.

7.1.2 Load duration curves

It is conventional to represent demand variation over the period of a year by load duration curves (also known as load exceedence curves). An example of a load duration curve is shown in figure 7.3. This shows that for a portion of the year λ, the load does not exceed a value L. This again disguises the effect of short duration peaks and obscures the number of plant starts required by the actual variations in demand. A crude measure of the desirability of a particular load duration curve is the system load factor (SLF) which is given by

$$\mathrm{SLF} = \frac{\text{total annual demand (GWh)}}{\text{8760 (hours) x annual peak demand (GW)}} \times 100\% \qquad (7.5)$$

A high system load factor indicates better (ie more cost effective) use of available plant. Thus a load duration curve such as shown in figure 7.4a is preferable to that shown in figure 7.4b although the quantity of electricity supplied is the same in each case.

However, SLF is a crude measure of the desirability of a particular load duration curve and figures 7.4c and 7.4d show two hypothetical curves with identical system load factors of which 7.4c is much to be preferred as a load duration curve since it offers the opportunity of much lower unit costs because a much higher proportion of high load factor plant may be used. In the case of 7.4c, 45% of the electricity demand occurs at load factors of 50% or higher, compared with only 30% in the case of d.

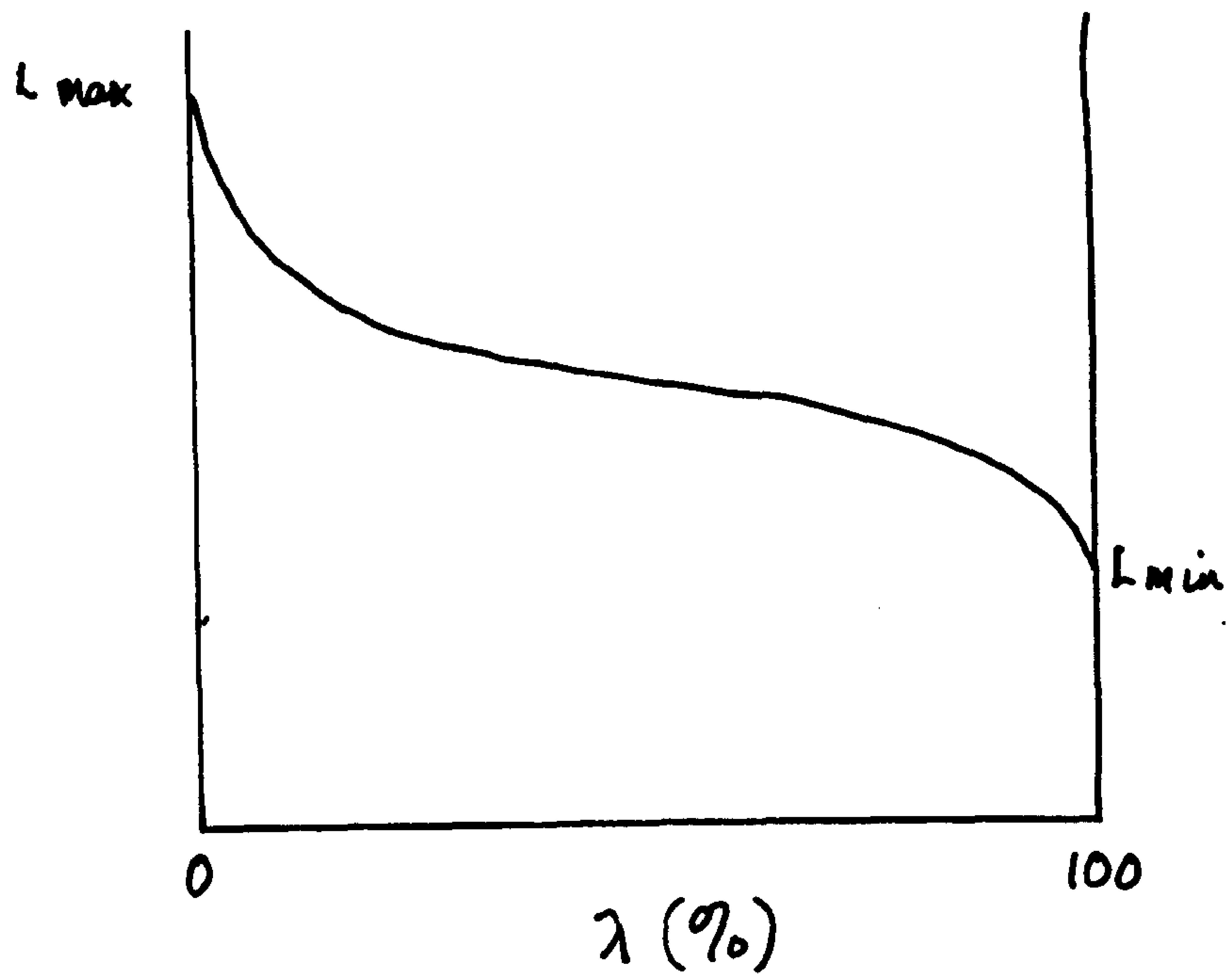

Figure 7.3 Annual load duration curve

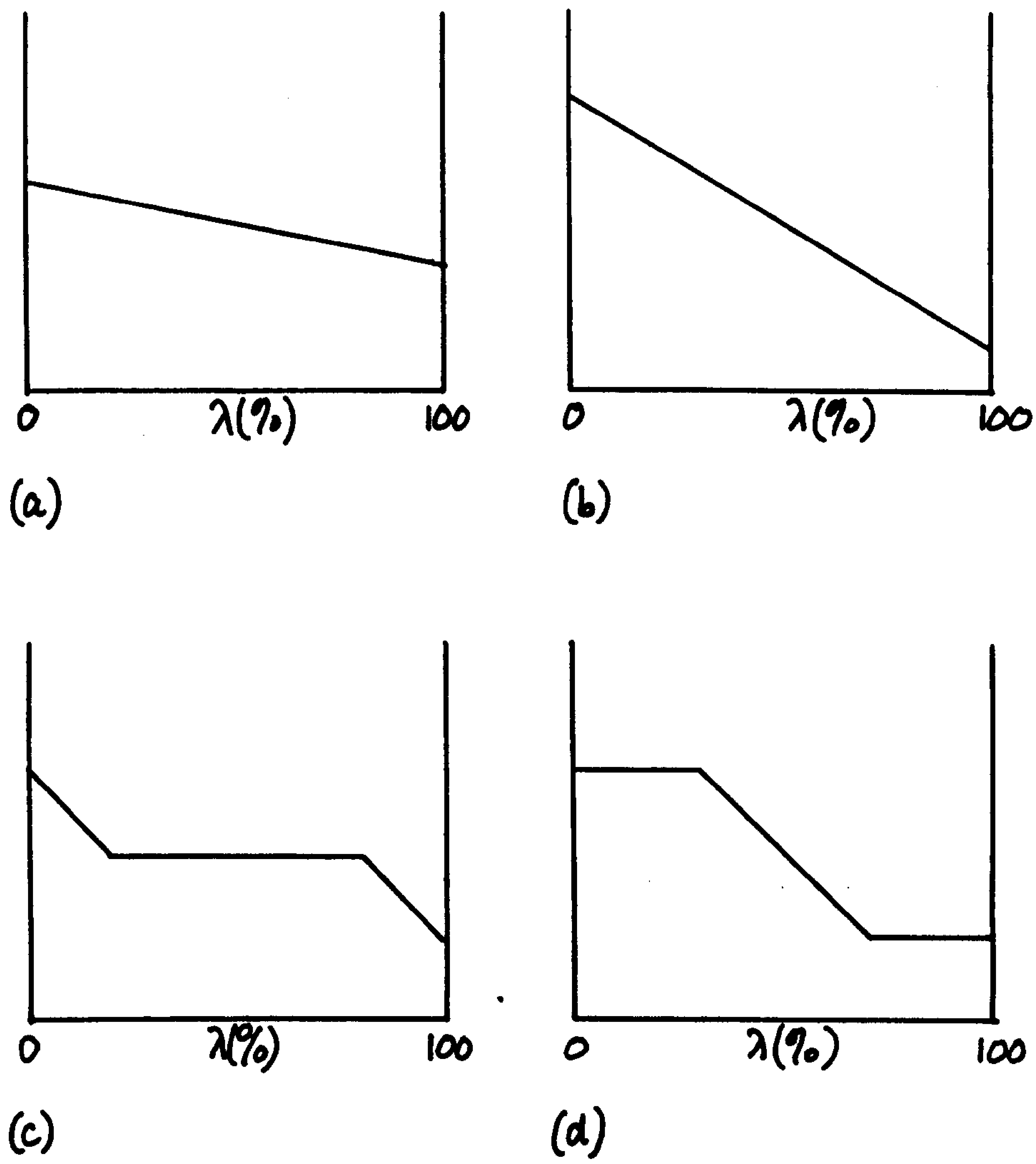

Figure 7.4 Sample load duration curves

The possibilities for 'designing' load duration curves is limited since it is the recorded or anticipated demand which is depicted. Demand manipulation as such is, in the UK confined to differential tariff structures. However, modification of technologies which leads to a change in the structure of electricity demand can be judged in the light of the changes induced in the annual load duration curve.

Load duration curves will be used in this study to determine the impact of CHP on the electricity generation system.

7.2 TREATMENT OF MERIT ORDER

The actual merit order varies on a day to day basis according to plant availability, current fuel prices and plant readiness. As an additional problem the merit order is confidential to the CEGB, making examination and analysis difficult.

7.2.1 De facto merit order

Since representation of the merit order is clearly necessary for this study as a means of determining inputs at particular demand levels it was necessary to find an alternative to the merit order used by the CEGB. An excellent alternative can be determined by reference to the CEGB's Statistical Yearbook (7.1). Here performance statistics of all the CEGB's power stations are recorded for 1977 including declared net capability (capacity), firing type (ie fuel input type), thermal efficiency and annual achieved load factor. It is this last figure, annual achieved load factor, which enables a 'de facto merit order' to be constructed. In other words it is assumed that power stations with a high load factor achieved that high load factor because they were high in the merit order and that, in another year, with the same set of power stations, they would continue to have a high load factor. This assumption would break down if there were a significant change in the relative prices of fuels or in the relative running costs of plant. Thus, by ranking all the 147 CEGB power stations in descending order of achieved load factor, a de facto merit order is constructed. Characteristics of power stations at different positions in the merit order are shown in Appendix 6. Note that the concept of a 'de facto' merit order explicitly recognises that some expensive-to-run plant may achieve higher load factors, because of fast response time, than might be expected by considering cost effects only.

Possible deviations from this de facto merit order would arise in the event of plant whose low load factor was attributable to commissioning during the year, a condition which would not be encountered during other possible years. This problem emerges only in the case of one small nuclear power plant in 1977. Subsequent decommissioning of plant need not be viewed as problematical since in all cases the basis of comparison of CHP technology is 1977 technology and the 1977 merit order.

The ranking of the 147 CEGB power stations was done by computer and an identifying flag was attached to each power station for subsequent analysis. The table of power station load factor against cumulative declared net capability is given in Table 7.1.

7.2.2 Calculation of inputs and outputs

No electricity plant has a station load factor of 100% because of planned and unplanned unavailability. For this reason, it requires installed capacity in excess of L Megawatts to supply a demand of L Megawatts. It is thus necessary to determine how the stations of the de facto merit order contribute to the load which makes up demand. This is a process requiring care in its detail and is described below. In summary the procedure adopted was

(a) determine the actual load duration curve for 1977

(b) determine the quantities of electricity supplied in each of a number of load bands

(c) by counting the outputs of the individual power stations in the de facto merit order, determine which power stations contribute power in each load band

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Load factor of last station in merit order	Total declared net capability
(%)	(MW)
90.4	420
80.3	2360
72.5	7774
64.0	13550
50.2	23971
40.1	32799
30.2	40326
20.0	44272
15.0	42960
10.4	45561
5.0	47222
0.1	56365

Table 7.1 CEGB Merit order derived from operating statistics

(d) by using the efficiency of each power station determine its fuel input for the year and hence the fuel input for each load band in 1977.

In effect, this is defining a number of different processes for electricity production which might be labelled 'electricity production between loads of L_n MW and L_{n+1} MW of demand'.

7.2.2.1 Determination of 1977 load duration curve

Like the merit order listing, the actual shape of the load duration curve is confidential to the Electricity Supply Industry. It thus becomes necessary to approximate one using the best available information. Two approaches are used.

The load duration curve used in this study is based upon one approximated in the Energy Research Group's Electricity Report (7.2). This was approximated on the basis of Electricity Council data. There are problems with this however since although the maximum and minimum demands shown are accurate the area under this curve does not correspond with the known electricity consumption for that year. This is a matter of 'massaging' a basically correct shape to correspond to the data. The data was adjusted according to the formula

$$\frac{L - L_{min}}{L_{max} - L_{min}} = \left(\frac{L' - L_{min}}{L_{max} - L_{min}}\right)^{\alpha} \qquad (7.6)$$

where L' is the load corresponding to the demand load factor as given in Electricity Report and L is the 'corrected' value of L. The exponent α was determined by trial and error until the area under the load duration curve was correct. The net effect is to 'bulge' the curve downwards to reduce the area under the Electricity Council curve by 7%. The load duration curve data and the curve are shown in table 7.2 and

λ, load factor of demand (%)	load (GW)	GWh delivered in load band	% of annual demand delivered at load factor greater than λ
100	9	78840	37.8
95	11.65	22627	48.7
90	14.32	21620	59.0
85	16.09	13624	65.5
80	16.98	6377	68.6
75	17.86	5985	71.5
70	19.19	8435	75.5
65	20.07	5202	78.0
60	21.39	7260	81.5
55	22.72	6674	84.7
50	23.59	4031	86.6
45	24.47	3643	88.4
40	25.79	4919	90.7
35	26.66	2868	92.1
30	27.54	2483	93.3
25	28.85	3173	94.8
20	30.17	2593	96.1
15	31.92	2698	97.4
10	33.69	1925	98.3
5	37.67	2618	99.5
0	42.10	970	100

Table 7.2 CEGB load duration curve data 1976/7

figures 7.5 and 7.6.

The curve derived by the above procedure was checked against a curve derived by an alternative procedure which is described in section 7.3.6.2 below. Agreement between the two curves was sufficiently good that the curve derived above can be used with considerable confidence.

7.2.2.2 Matching power stations to the load duration curve

To determine the way in which the load is met, the load duration curve and the power station merit order list are brought together.

The incremental contribution to load made by each power station may be represented in the load duration curve by horizontal bands whose area corresponds to the output of the power station making the load contribution. Thus the contribution made by the station which is first in the merit order (m = 1) appears as the first of the bands at the bottom of the area under the load duration curve and the area of the first band has an area a_1, where a_m is the output of the m'th station in the merit order. The average load contribution to demand load is thus

$$L_m = L_d - L_{d-1} = \frac{\lambda'_m \times (\text{declared net capability})_m}{\frac{1}{2}(\lambda_{d-1} + \lambda_d)} \qquad (7.7)$$

where λ'_m is the load factor of the power station m, and λ_d is the load factor of demand corresponding to the load L_d (see figure 7.7) which is contributed by all the stations in the merit order list, up to and including station m. Note that L_m is the <u>average</u> load contributed by power station m over the year, in other words, it might well be less than the power station can provide, but taken together with stations m-2, m-1, m+1 and m+2 etc. L_m will be station m's share of the aggregated load contribution. So, this load contribution approach should not be taken to provide reliable information about individual

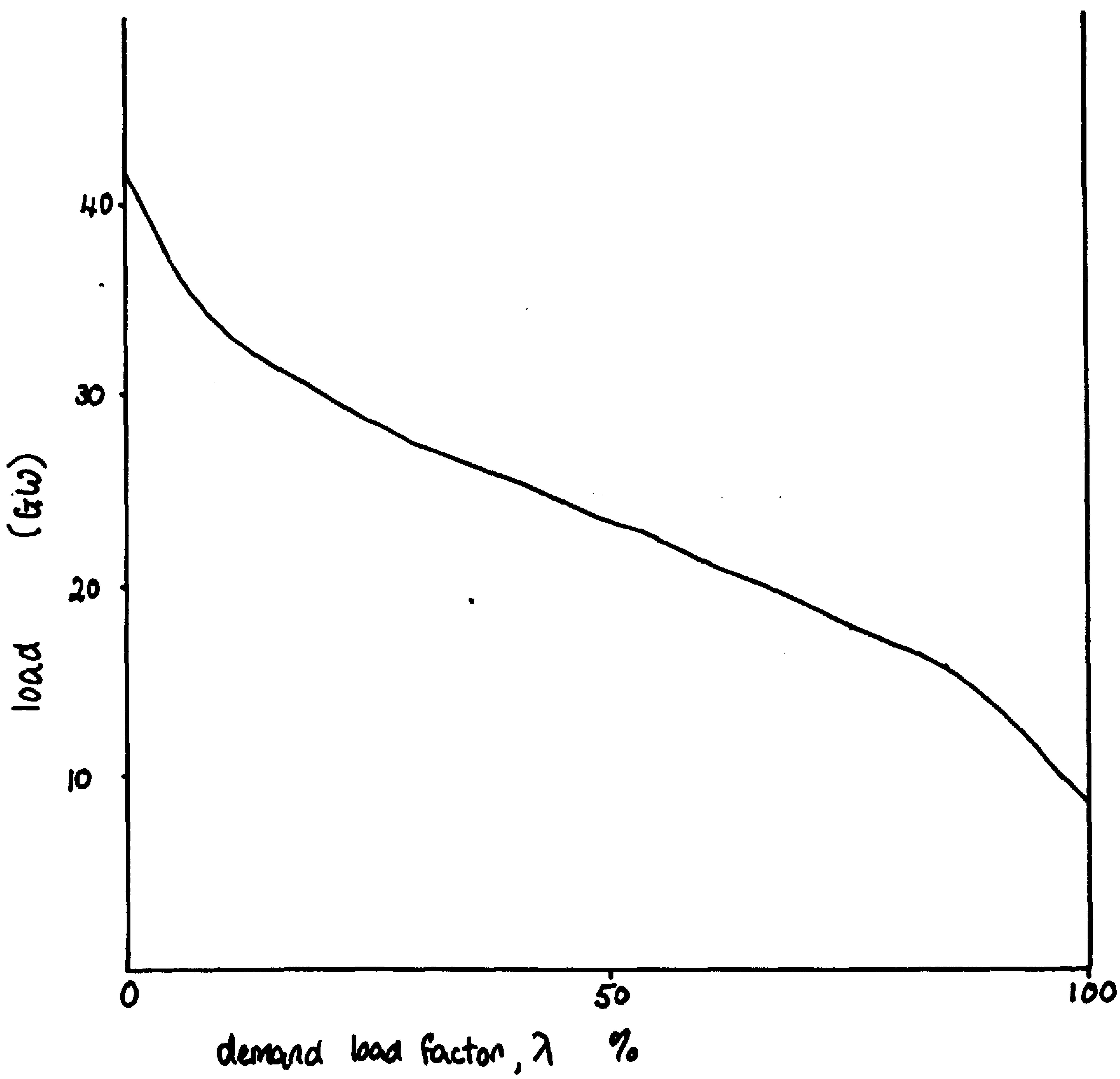

Figure 7.5 CEGB load duration curve 1976/7

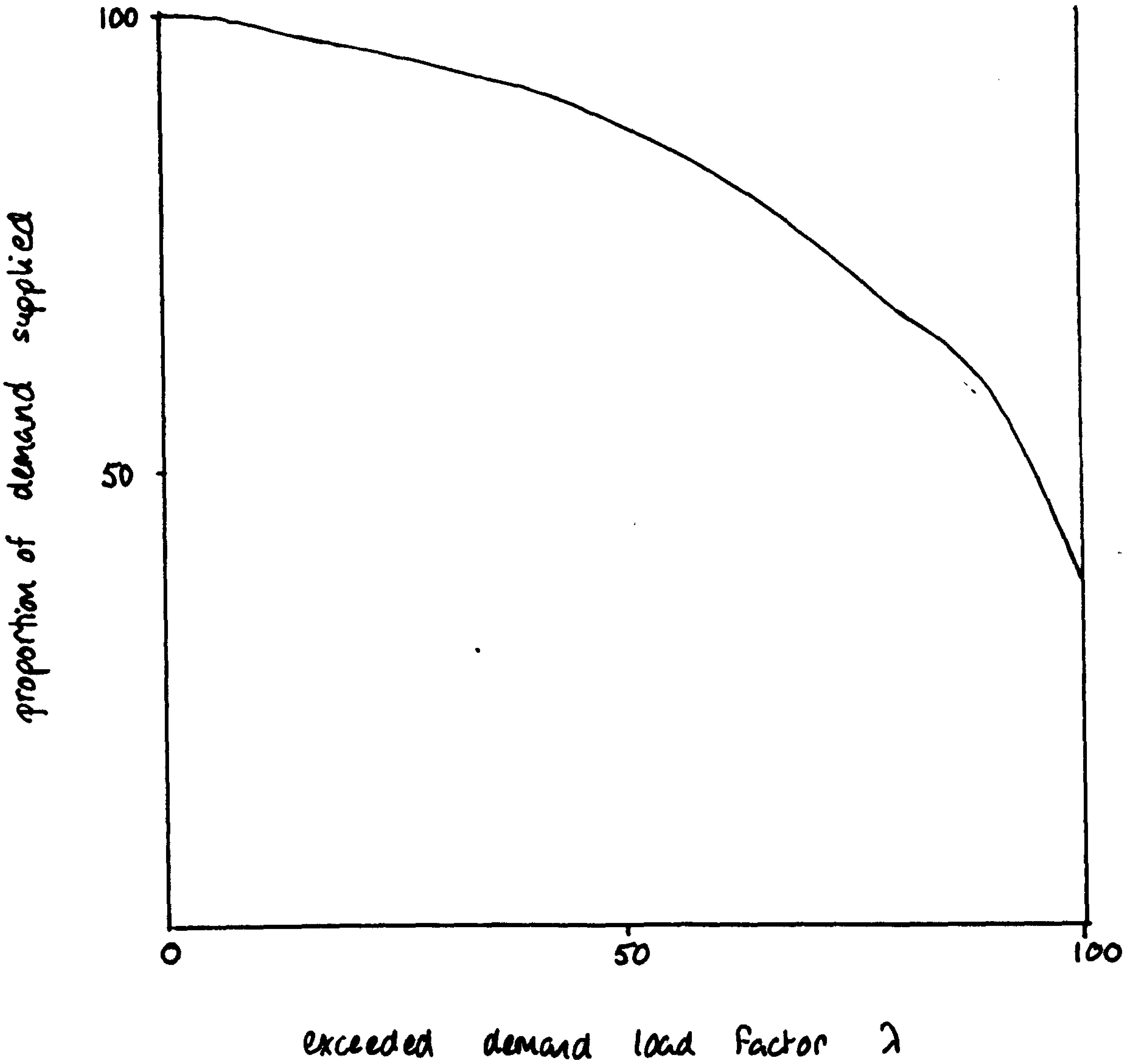

Figure 7.6 Cumulative demand curve CEGB (1976/7)

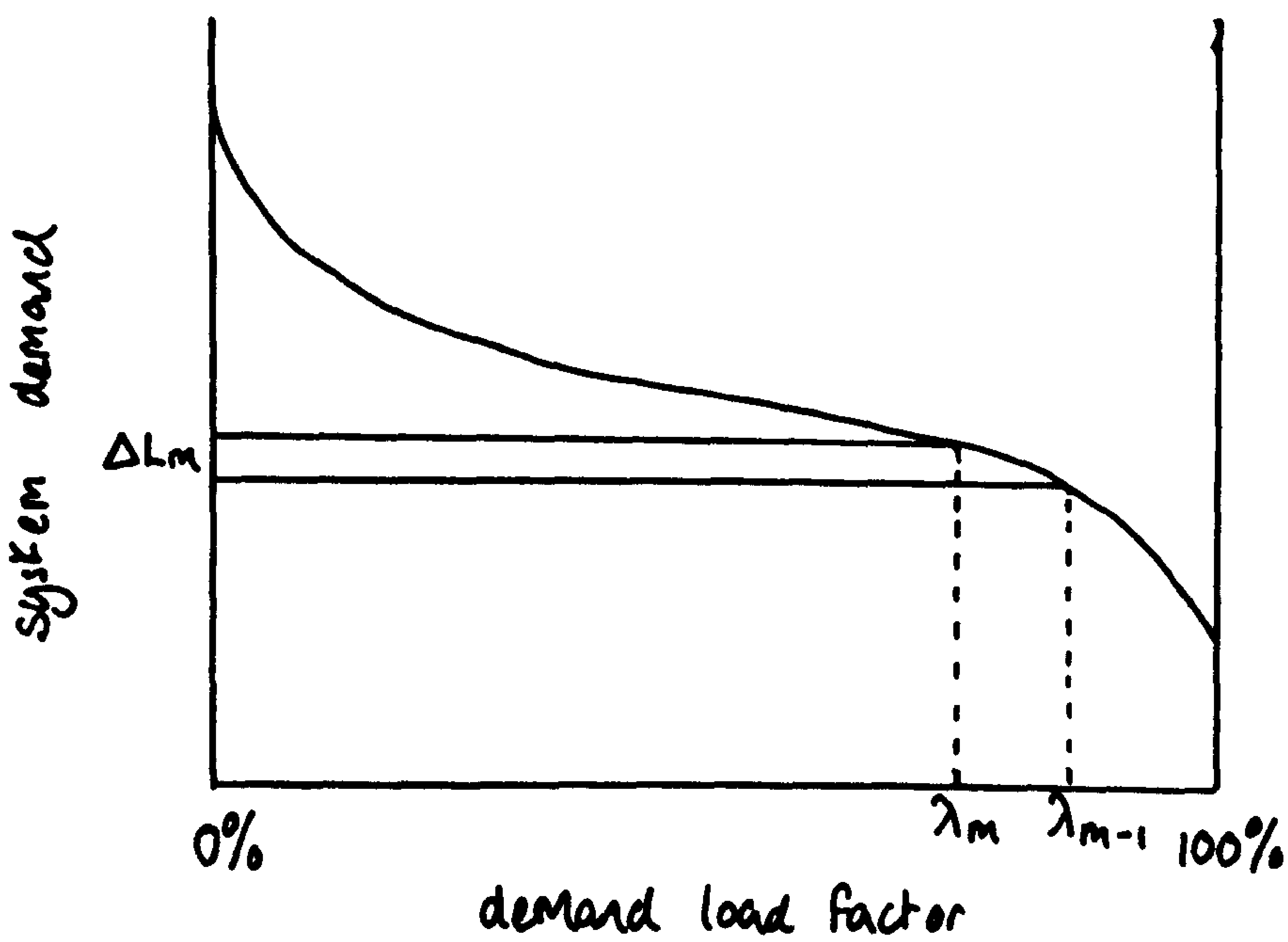

Figure 7.7 Load contribution by m'th station in merit order

power stations so much as about aggregated groups. The CEGB merit order data is presented in tables 7.3 and 7.4 and in figure 7.8.

Using this data it is easy to determine the inputs and outputs required to meet the load at any level of demand, obtaining data from the merit order listings. This is represented visually in figure 7.9 which shows the contribution made by each type of station to any load.

7.2.2.3 Treatment of Scotland and N. Ireland electricity production

Load duration curves are not additive, neither can a joint merit order be compiled for the CEGB, the Scottish Boards (South of Scotland Electricity Board and North of Scotland Hydro-Electric Board) and NIES (Northern Ireland Electricity Service) simply by sorting a combined listing of power station load factors. The means by which data can be obtained for the system as a whole is described below.

The problem of the non additive nature of the load duration curve and the merit order listings is resolved by treating the CEGB, the Scottish Boards and NIES as three separate entities. The Scottish Boards can be treated together since they operate generation capacity as one integrated system.

The procedure for determining the inputs to each load band for the CEGB is described above. The Scottish load duration curve was approximated by assuming it to be a similar shape to that of the CEGB and scaling between the known maximum and minimum loads. The area under the curve derived by this method was found to be within 20% of the known output of Scottish electricity. The 'bulging' procedure described above for the CEGB curve was used to determine the appropriate curve for Scotland.

Load (GW)	GWh delivered (load duration curve)	GWh delivered (merit order list)	number of stations contributing to load
9	78840.	86504.6	15
11.6492	101467.	101921.	20
14.3174	123087.	127257.	25
16.0949	136711.	139081.	29
16.9772	143088.	143689.	32
17.8588	149073.	152002.	34
19.1869	157508.	157627.	37
20.0667	162710.	164203.	38
21.3928	169971.	170421.	41
22.7177	176644.	177435.	44
23.5943	180676.	181516.	48
24.4698	184319.	187977.	51
25.791	189237.	189409.	53
26.6641	192106.	192383.	57
27.5362	194588.	194783.	59
28.8533	197761.	198332.	67
30.1689	200354.	200532.	70
31.9289	203053.	203097.	80
33.687	204978.	205166.	89
37.6719	207596.	207599.	114
42.1	208565.	207893.	147

Table 7.3* Matching power plant to load contribution

*Note that, although there were only 138 power stations in the CEGB system, 147 separate items of plant are listed in the de facto merit order since some stations have associated gas turbine plant operating separately from the steam plant.

demand load factor	load factor of last power station in merit order
100	64
95	53.9
90	51
85	48.3
80	45.2
75	43.9
70	41.3
65	40.8
60	37.2
55	35.6
50	33.7
45	32.3
40	30.8
35	28
30	25.7
25	21.7
20	19.3
15	16
10	12.5
5	2.2
0	.1

Table 7.4 Demand load factor and station load factors

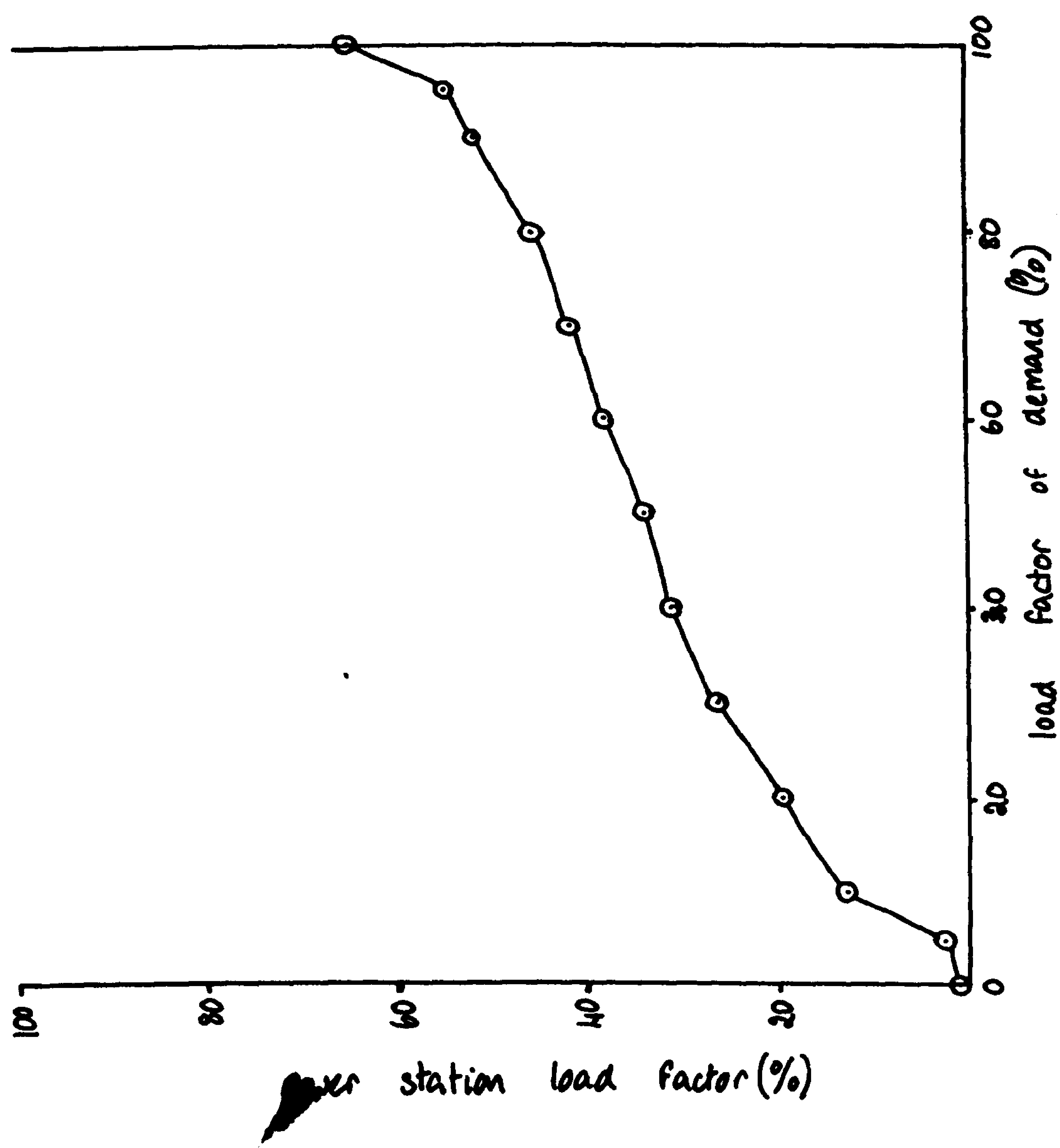

Figure 7.8 Station load factor and load factor of demand

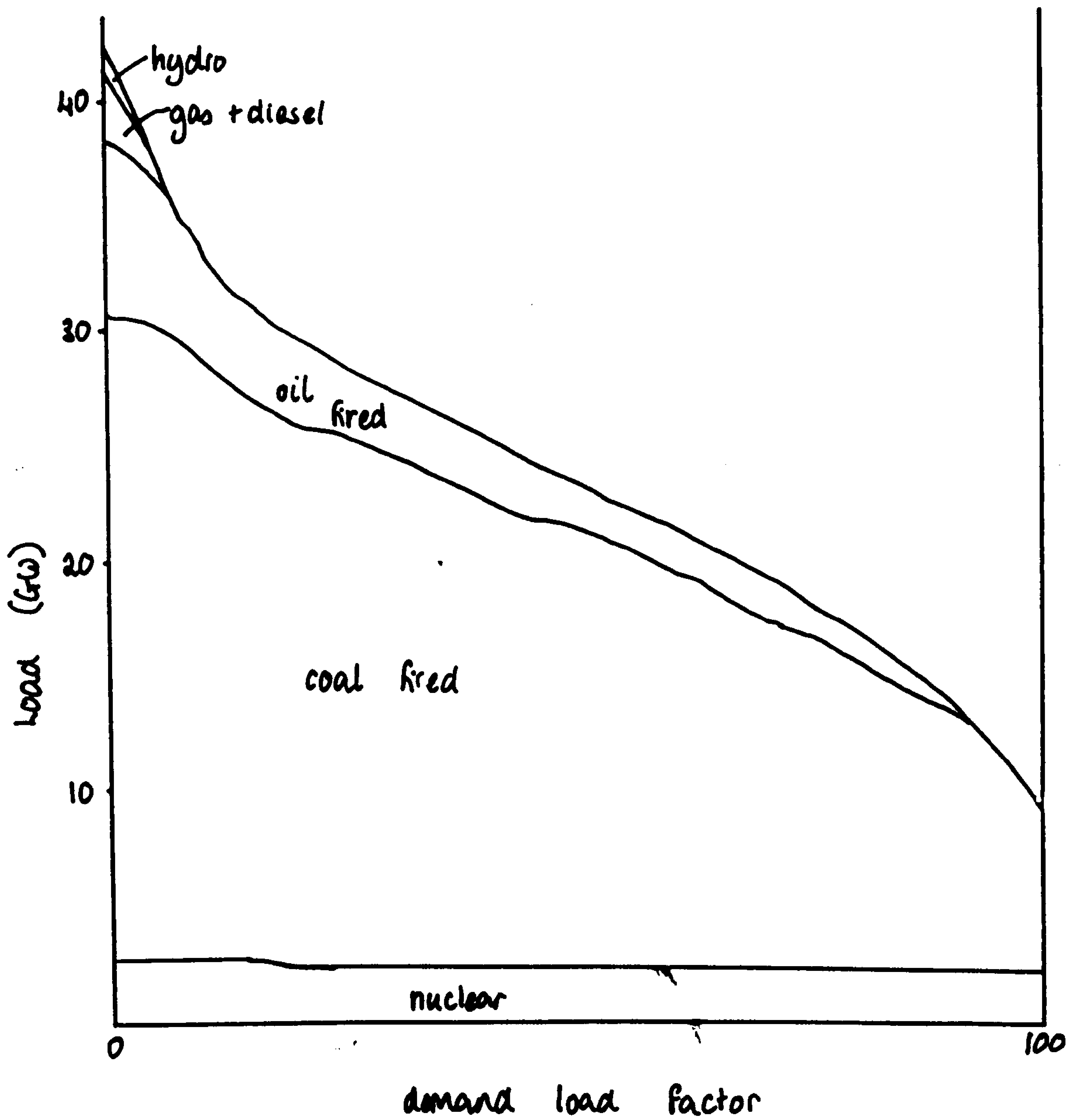

Figure 7.9 Composition of load duration curve

The Scottish load duration curve (data list in table 7.5) was split into load bands corresponding to the same load factor ranges as for the CEGB (see tables 7.6 and 7.7). The inputs to each load band were determined for Scotland, as for the CEGB, by dividing output by efficiency for each station and multiplying by the appropriate value.

The total inputs for both CEGB and Scottish Boards was checked against fuel purchase data and was found to be acceptably close (± 5%).

Only 4% of UK electricity consumption occurs in Northern Ireland. Because this is such a small proportion, the electricity produced by NIES is treated as middle order production and no matching of power stations and load bands was attempted.

The final 'combined' data set was arrived at by adding the load increment achieved between two demand load factors by the CEGB to that achieved by the Scottish Boards between the same two load factors. The combined load duration curve data is shown in table 7.8. Input data is recorded in tables 7.9, 7.10 and 7.11.

While the procedure adopted above has some advantages as a means of treating the two electricity systems, it has some disadvantages. Firstly it still treats the load duration curves of the two systems as being additive. In particular this implies that annual peak loads and annual minimum loads occur simultaneously in both CEGB and Scottish systems. This problem can only be fully overcome by treating 'CEGB electricity' and 'Scottish electricity' as completely separate commodities, a course which was rejected in this study because of the already large matrix (eventually 112 x 112; see Appendix 9 below). However, part of the disadvantages of making this assumption have been removed by assigning

λ, load factor of demand (%)	load (GW)	GWh delivered in load band	% of annual demand delivered at load factor greater than λ
100	1.24	10862	43.38
95	1.39	1245	48.3
90	1.62	1873	55.7
85	1.80	1391	61.3
80	1.89	698	64.1
75	2.00	682	66.8
70	2.15	1006	70.8
65	2.26	645	73.4
60	2.43	934	77.1
55	2.61	892	80.6
50	2.73	554	82.9
45	2.85	512	84.9
40	3.04	710	87.7
35	3.17	423	89.4
30	3.30	373	90.9
25	3.51	487	92.8
20	3.71	408	94.5
15	4.00	436	96.2
10	4.29	320	97.5
5	4.98	454	99.3
0	5.79	177	100.0

Table 7.5 Scottish Boards' load duration curve 1976/7

demand load factor range (%)	L (GW)	ΔL (GW)	GWh in load band
100 - 100	5	5	43790
100 - 100	9	4	35050
100 - 65	20.07	11.07	83870
65 - 20	30.17	10.10	37644
20 - 0	42.10	11.93	8221

Table 7.6 Output in each load band (CEGB)

demand load factor range (%)	L (GW)	ΔL (GW)	GWh in load band
100 - 100	0.69	0.69	6035
100 - 100	1.24	0.55	4828
100 - 65	2.26	1.02	7540
65 - 20	3.71	1.45	5294
20 - 0	5.79	2.08	1386

Table 7.7 Output in each load band (Scottish Boards)

demand load factor range (%)	L (GW)	ΔL (GW)	GWh in load band
100 - 100	5.69	5.69	49825
100 - 100	10.24	4.55	39878
100 - 65	22.33	12.09	91410
65 - 20	33.88	11.55	42938
20 - 0	47.89	14.01	9607

Table 7.8 'Combined' load duration curve data derived from tables 7.6 and 7.7

demand load factor range (%)	output: electricity (GWh)	inputs: † coal (mtonnes)	oil†† (ktonnes)	gas (Mtherms)
100 - 100	43790	10.01	0	0
100 - 100	35050	14.18	0	33
100 - 65	83870	28.81	4462	90
65 - 20	37644	14.23	2629	3
20 - 0	8221	29.03	881	2

† excludes nuclear heat and available heat for hydro power

†† including diesel

Table 7.9 Inputs to each load band (CEGB)

demand load factor range %	output: electricity (GWh)	inputs:†		
		coal (mtonnes)	oil (ktonnes)††	gas (Mtherms)
100 - 100	6035	2.80	619	-
100 - 100	4828	2.45	540	-
100 - 65	7540	3.63	796	-
65 - 20	5290	1.20	25	-
20 - 0	1386	-	221	-

† excludes nuclear heat and available head for hydropower

†† including diesel

Table 7.10 Inputs to each load band (Scotland)

load band (GW)	demand load factor range %	output: electricity (GWh)	inputs:†		
			coal (mtonnes)	oil (ktonnes)††	gas (Mtherms)
0- 5.69	100 - 100	49825	12.81	619	0
5.69-10.24	100 - 100	39878	16.63	540	23
10.24-22.33	100 - 65	91410	32.44	5258	90
22.33-33.88	65 - 20	42938	14.43	2654	3
33.88-47.89	20 - 0	9607	29.03	1102	2

† excludes nuclear heat and available head for hydropower

†† including diesel

Table 7.11 Inputs to each load band (CEGB and Scotland) inputs (ie power stations) to load bands separately, thus avoiding the mistake of implying that peak demand on the Scottish system is met by plant demand of the type contributing to baseload in the CEGB system.

7.2.2.4 Input and output data

The simple non linearity of the electricity production system (as exempified by equation 7.2) may be described by describing the production of electricity at different load levels as production of electricity by a number of different processes which are used in turn until the appropriate load level is reached. Using the data presented in table 7.11 this would work as follows. At loads up to 5.69 GW one electricity production process (called 'Base load I') operates. Base load I has the same ratio of inputs to outputs as are shown in Table 7.11. If the load required exceeds 5.69 GW but does not exceed 10.24 GW, then Base load I operates at an activity level defined as 1 and a second process, 'Base load II' operates at whatever level of activity is required to complete the requirement for electricity. When the activity level required of Base load II exceeds 1 then the activity level of Base load II is constrained to be one and the constraint keeping the activity level of 'Low load middle order' is removed and allowed to find its own level.

Note that this approach can only be used where the time period t during which electricity is required is such that the load during that period can be modelled as constant. In other words this approach can only deal with simple non linearity for the type of demand variation illustrated by the load duration curves, figures 7.1(a) and 7.1(b). An extention of the approach to deal with dynamic non linearity is described in section 7.3 below but it is important that the technique for simple non-linearity is appreciated since it forms a part of the approach to dynamic non-linearity.

The input-output ratios for each of the five load bands described in Table 7.11 are used to specify five electricity production processes, known as 'base load I', 'base load II', 'low load middle order', 'high load middle order' and 'peak'.

The convention adopted in the model described in Chapters 4, 5 and 6 is that the activity levels of processes was one or zero for 1977 production levels. In specifying elements for the full scale matrix this convention has not been observed. Considerable advantages arise from using an alternative convention where, for each load band/process an activity level of one corresponds to an average load factor of 100% in the band. In other words for the process operating to produce electricity between loads L_n and L_{n+1} (GW), the activity is defined as being one where the total annual output from that process is $(L_{n+1} - L_n) \times 8760$ GWh. Thus the activity level x for that band is given by

$$x = \frac{\text{GWh supplied}}{(L_{n+1} - L_n) \times 8760} \tag{7.8}$$

In this way the activity level corresponds to the average load factor of demand in that band. Not only is this a convenient feature in itself but it carries the additional advantage that the demand level at which load exceeds the maximum that can be supplied by the band process (ie λ = 100%) can be identified when the corresponding activity level is equal to one; a simple condition to recognise. This would not be possible were the original convention adhered to for the electricity production process.

To normalise the data of Table 7.11 to provide data for the expanded matrix, the <u>average</u> load factor of demand was determined for each band. Both inputs and outputs in each band were divided by this number to produce equivalent 100% load factor data in each load band. This is shown in table 7.12.

An example of the use of a small matrix using this data is shown in Appendix 7.

7.3 MODELLING LOAD VARIATION WITH TIME

As already remarked, the procedure for dealing with non-linearity in the electricity production process is adequate for the time period t, provided that during the time period t the electricity load is constant, as illustrated in figures 7.1(a) and 7.1(b). Clearly where t is one year the model is far from adequate and must be modified still further to take account of the variability of load within the year.

7.3.1 Time-flagged electricity

It has already been noted that to all intents and purposes there is no capability within the UK for storing electricity, either at the local level by consumers nor by the electricity producers. Thus electricity demanded at time t_i cannot be purchased at time t_j nor can electricity supplied at time tm be consumed at any other time t_n either before or after.

Since in the matrix model it is implicit that commodity i produced during the year can be consumed at any time during the year then in order that the model of electricity production be compatible with the rest of the matrix description, electricity must be flagged to show the time period during which it is available. Twelve 'types' of electricity have thus been specified which are not substitutable for or interconvertable with each other, each of the twelve types being known as 'electricity at time period k' where k = 1 to 12. The division of the year into twelve characteristic time periods is described in section 7.3.3 below.

process	load band (GW)	average load factor of demand	output (GWh)	inputs		
				coal (mtonnes)	oil (ktonnes)	gas (Mtherms)
baseload I	0- 5.69	100%	49835	12.88	619	-
baseload II	5.69-10.24	100%	39868	16.63	540	167
low load middle order	10.24-22.33	86.3%	105879	37.60	6100	516
high load middle order	22.33-33.88	42.43%	101197	33.74	62138	60
peak	33.88-47.89	7.83%	122737	36.88	14105	296

Table 7.12 Process data for expanded matrix (normalised to λ = 100%)

7.3.2 Production of time flagged electricity

The method by which each non-substitutable 'type' of electricity is produced will depend upon the magnitude of demand for electricity during the time period concerned. The production of 'electricity at time period t_n' thus becomes a simple non-linear process of the type described in section 7.2, if the time periods are chosen in such a way that the demand for electricity during time period t_n can be modelled as constant. In this way a demand for 'electricity at time period t_n' can be satisfied by operating merit order bands of stations to their full capacity during the time period until the level of demand is met.

In the commodity process matrix, this is represented by splitting each of the five electricity production processes specified in section 7.2. into twelve sub processes representing production of electricity in each of the twelve time periods. This gives 60 electricity production processes in all. Since each of the time periods used is of equal length, this means that each element was divided by twelve. Table 7.13 illustrates how this works for the low load middle order load band.

Splitting electricity and the electricity production processes in this way gives 60 electricity production processes producing 12 different types of electricity. Forty eight constraints are then required in order to determine a unique inverse. Groups of four of these constraints describe the production of each type of electricity as described in section 7.2 above. Since each group of four constraints does not interact directly with any other group it is still relatively easy to find the activity level of each process such that $0 \leqslant x_j < 1$.

The <u>overall</u> activity level of each production process, representing the annual activity level of the overall process (as represented in table 7.12) is the average of the twelve activity levels of the constituent

	low load middle order (t_1)	low load middle order (t_2)	low load middle order (t_3)	low load middle order (t_4)	low load middle order (t_5)	low load middle order (t_6)	low load middle order (t_7)	low load middle order (t_8)	low load middle order (t_9)	low load middle order (t_{10})	low load middle order (t_{11})	low load middle order (t_{12})	
coal	-3.13	-3.13	-3.13	-3.13	-3.13	-3.13	-3.13	-3.13	-3.13	-3.13	-3.13	-3.13	mtonnes
oil	-508	-508	-508	-508	-508	-508	-508	-508	-508	-508	-508	-508	th.tonnes
gas	-43	-43	-43	-43	-43	-43	-43	-43	-43	-43	-43	-43	M.therms
electricity at time t_1	8823	-	-	-	-	-	-	-	-	-	-	-	GWh
electricity at time t_2	-	8823	-	-	-	-	-	-	-	-	-	-	GWh
electricity at time t_3	-	-	8823	-	-	-	-	-	-	-	-	-	GWh
electricity at time t_4	-	-	-	8823	-	-	-	-	-	-	-	-	GWh
electricity at time t_5	-	-	-	-	8823	-	-	-	-	-	-	-	GWh
electricity at time t_6	-	-	-	-	-	8823	-	-	-	-	-	-	GWh
electricity at time t_7	-	-	-	-	-	-	8823	-	-	-	-	-	GWh
electricity at time t_8	-	-	-	-	-	-	-	8823	-	-	-	-	GWh
electricity at time t_9	-	-	-	-	-	-	-	-	8823	-	-	-	GWh
electricity at time t_{10}	-	-	-	-	-	-	-	-	-	8823	-	-	GWh
electricity at time t_{11}	-	-	-	-	-	-	-	-	-	-	8823	-	GWh
electricity at time t_{12}	-	-	-	-	-	-	-	-	-	-	-	8823	GWh

Original data (section 7.2)

	low load middle order
coal	37.60 m.tonnes
oil	6100 th.tonnes
gas	516 Mtherms
electricity	105879 GWh

Table 7.13 Low load middle order production processes for time flagged electricity

time flagged processes. Thus the 1977 technology scenario generates the set of process activity levels shown in table 7.14. This corresponds to annual activity levels for each of the load band activity levels as shown in table 7.15. The significance of these activity levels will be described below in section 7.3.6.1. A number of further features of the calculated activity levels can be discerned. If constraints are properly applied, that is high merit order plant is used first in meeting a load then if $0 < x_j < 1$, then $x_{j-12} = 1$, and $x_{j+12} = 0$, where processes j-12 and j+12 are electricity production processes. Processes m+12n, where $1 \leqslant m \leqslant 12$ and $0 \leqslant n \leqslant 4$, all refer to electricity produced during time period t_m. Merit order band n + 1 is the marginal source of electricity during the time period t_m. The largest entry in the activity level list in the range j = 89 to 100 (or exceptionally 77 to 88 where all entries in the range 89 to 100 are zero) denotes peak demand and the time period during which it occurs may be determined.

7.3.3 Selection and specification of characteristic time periods

The selection of characteristic time periods to represent annual variation in demand is severely constrained by the necessity to keep the order of the matrix within acceptable limits and by the availability of credible data (or the ability to invert plausible data). Twelve periods seems to be an optimum balance between coarseness of representation and spurious accuracy. However, the accuracy that can be achieved with only twelve time periods will not be very great and so the time periods were selected with the primary objective of yielding the maximum possible information.

It is clear that the time periods chosen as characteristic of annual load levels should meet the following criteria:

Process number	Activity level	Process number	Activity level	Process number	Activity level
41	1	61	1	81	0.7742
42	1	62	1	82	1
43	1	63	1	83	0
44	1	64	1	84	0
45	1	65	1	85	0.2556
46	1	66	1	86	0
47	1	67	1	87	0.0764
48	1	68	0.5130	88	0.4366
49	1	69	1	89	0
50	1	70	1	90	0
51	1	71	0.1969	91	0.7052
52	1	72	0.9018	92	0
53	1	73	1	93	0
54	1	74	0.7248	94	0.2542
55	1	75	1	95	0
56	1	76	1	96	0
57	1	77	0.6028	97	0
58	1	78	0.9940	98	0
59	1	79	1	99	0
60	1	80	0	100	0

Table 7.14 Electricity production process activity levels

Explanatory note: Processes 41-52 Baseload I
Processes 53-64 Baseload II
Processes 65-76 Low load middle order
Processes 77-88 High load middle order
Processes 89-100 Peak

Process	Overall process activity level
Baseload I	$\sum_{41}^{52} x_j/12 = 1$
Baseload II	$\sum_{53}^{64} x_j/12 = 1$
Low load middle order	$\sum_{65}^{76} x_j/12 = 0.8614$
High load middle order	$\sum_{77}^{88} x_j/12 = 0.4283$
Peak	$\sum_{89}^{100} x_j/12 = 0.0800$

Table 7.15 Overall process activity levels derived from Table 7.14

1. Should give the 1977 maximum demand
2. Should give the 1977 minimum demand
3. Should have a total electricity demand equal to the annual electricity demand
4. Should give a reasonable approximation to the 1977 load duration curve

For convenience, it was decided that the time periods should represent equal portions of the year although there is no necessity for this. Hour by hour load variation for one year was approximated using the model developed by Baker (7.3). This model assumes that the shape of the daily load demand remains the same throughout the year. The total load at any given time of a given day is found by multiplying that day's average load by the appropriate fraction for that time of day. Average daily load is modelled as varying sinusoidally through the year. The two seasonal factors for the sinusoidal fraction were determined by Baker from a best fit for quarterly electricity sales data. Thus, according to Baker:

$$L(t,d) = D\{1 + A\cos(2\pi d/365) + B\sin(2\pi d/365)\}f(t) \quad (7.9)$$

where D is the annual average load

f(t) is the load at time t as a proportion of the average daily load

A, B are seasonal factors

L(t,d) is the total load at time t on day d

While this approach makes the variation in electricity demand accessible to analytical treatment, it is of course a less accurate representation of load variation than is available as a direct record of the CEGB's and Scottish Boards' experience. In particular there is no provision within this model for representing 'weekend effects'. However, the simplicity of this approach offers considerable advantages without prejudicing the possibility of using improved data in future work.

Values for f(t) in equation 7.9 above are tabulated by Baker (7.3). A and B are determined by inserting approximate data for peak and minimum annual demand.

The hour by hour load levels calculated by the Baker model were examined and twelve of the hourly load levels were selected by trial and error to represent the prevailing load level for one twelth of the year ie for one of the twelve time periods. The time periods described above should therefore be understood as representing one twelth of the year which need not occur in one block but may be distributed throughout the year. The twelve characteristic demand levels which were found to meet the criteria 1 to 4 set out above were those calculated by the Baker model to occur at each of the hours 0200, 1000 and 1800 on each of the midwinter, midsummer, mid-spring and mid-autumn days. The loads occuring at each of these twelve times are thus used to represent loads occurring for one twelth of the year. The data generated is shown in table 7.16. The actual values of the loads during the characteristic time periods is determined by taking twelve vertical slices of equal width from the load duration curve as shown in table 7.17.

The specification of the characteristic time periods is completed by attributing to each of the load levels in table 7.17 a time and day which aids in specifying the time of occurrence of particular load levels and in attributing sources of demand as shown in section 7.3.4 below. This is done by ordering the loads of table 7.16 in ascending order. This

day/hour	Baker's model output (GW)	size ordering (1 = largest)
15/2	32.9	5
15/10	34.0	3
15/18	39.0	1
106/2	20.7	11
106/10	37.4	4
106/18	34.9	2
197/2	9.4	12
197/10	25.4	9
197/18	27.3	7
288/2	20.4	10
288/10	26.7	8
288/18	30.3	6

Table 7.16 Load/time data generated using Baker's (7.3) model

load factor (% of year)	load (GW)	average load (GW)	electricity generated (av. load x 8760/12 (GWh)
100	10.24		
		12.62	9212.6
91.67	14.99		
		16.44	12001.2
83.33	17.89		
		19.00	13870.0
75.00	20.11		
		21.14	15432.2
66.67	22.17		
		23.21	16943.3
58.33	24.24		
		25.28	18454.4
50.00	26.32		
		27.37	19980.1
41.67	28.41		
		29.29	21381.7
33.33	30.17		
		31.27	22827.1
25.00	32.36		
		33.81	24681.3
16.67	35.25		
		37.44	27331.2
8.33	39.63		
		43.76	31944.2
0	47.89		

Table 7.17 Average load in time periods of one twelfth of a year (1977 load duration curve data)

enables us to draw broad conclusions about data such as 'the annual peak load occurs at around 6pm on a midwinter day' or 'the minimum peak load occurs overnight in midsummer'. While this information appears to be trivial for the 1977 state of technology, it is noted that under certain assumptions about CHP/dh technology these times change.

7.3.4 Time specification of demand

It is now necessary to specify the constituent components for the demand for time flagged electricity. This was done by making some assumptions about whether processes work one, two or three shift operations and the extent to which demand is seasonal. Fuller details are given in Appendix 8. Each process for which electricity is an input has that electricity input specified in terms of the time periods during which the electricity is required.

7.3.5 Transmission processes

As in the pilot study an electricity transmission process was specified, so in the full-scale study twelve electricity transmission processes were specified to account for transmission losses and as a means of summing the electricity produced during each time period.

7.3.6 Determination of load duration curves

As described above, the effect upon the shape of the load duration curve is the principal method of determining the effect of CHP/dh upon the electricity industry and so the load duration curve must be capable of determination from the calculated vector of activity levels. This can be done in two independent ways.

7.3.6.1 Electricity production process activity levels

The annual activity level for each of the five electricity production processes can be determined by summing the activity levels of that process for each of the twelve time periods and dividing by twelve (see section 7.3.2 above). A five point representation of the load duration curve can be determined by multiplying each of these annual activity levels by 100% to give the load factor of the load band concerned. The coordinates on the load (vertical) axis are then 2.84GW, 7.96GW, 16.28GW, 28.10GW and 40.88GW being the mean loads of each load band at 100% load factor.

7.3.6.2 Transmission process activity levels

A twelve point approximation to the load duration curve may be obtained directly from the process activity levels determined for the twelve transmission processes. Since these are normalised to 730GWh/annum the activity level for each transmission level is given in GW. If the activity levels for the transmission processes are arranged in descending order then an approximate load duration curve can be drawn. The load duration data calculated by this method is compared with the load duration curve derived in section 7.1.2 in figure 7.10.

7.4 CHP/dh TECHNOLOGIES

It follows from the foregoing discussion that the electricity output from CHP/dh plant must be time flagged. Since time of production is a new feature of the model, it also follows that some assumptions about the storability (or otherwise) of the heat produced by CHP or HOB plant must now be made. In practice, as soon as storage of heat between time periods is permitted then the range of possible modes of operation of CHP plant becomes very large. This may be illustrated by consideration of the two extreme assumptions about the storability of heat.

7.4.1 No heat storage

At this extreme, it is assumed that heat generated in one time period can only be used by heat consumers during that period. At this extreme heat

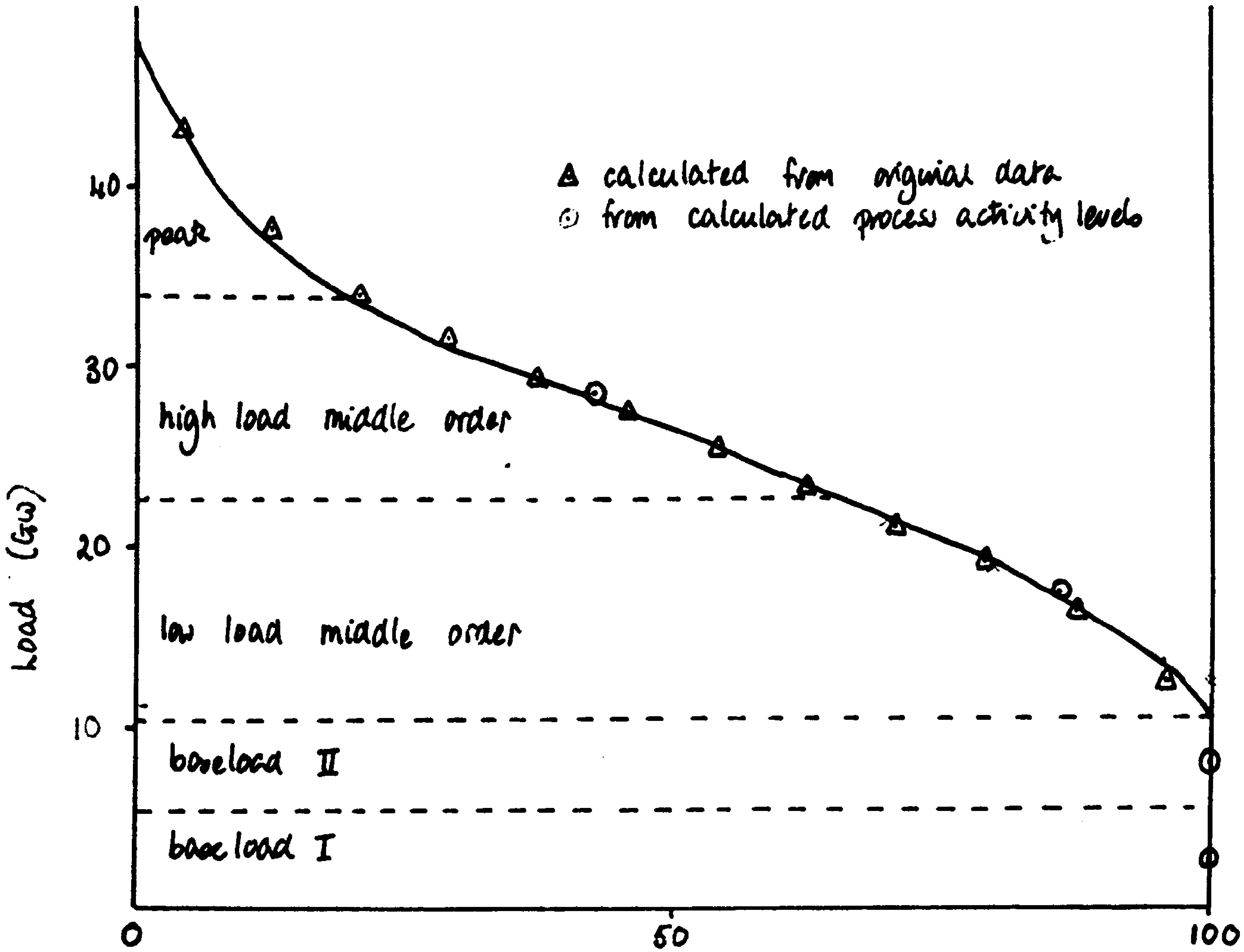

Figure 7.10 Load duration curve (1977)

is the premium product of CHP plant whose operation during any time period is dictated solely by the requirement for heat during that period. Electricity is truly a by-product. The power stations, in this scenario, operate so as to meet the shortfall in electricity requirements. Twelve types of heat are specified, in a manner similar to that for electricity. If the penetration of CHP into the domestic and commercial heat markets is specified by constraints then no further constraints are required to specify the operation of the CHP plant.

7.4.2 Total heat storage

At the other extreme only one heat commodity need be specified although twelve CHP processes must be specified, to allow for the production of twelve different types of electricity. In this case, even if the penetration of district heating into the heat market is specified, eleven further constraints are required to place the CHP process in relation to other electricity production processes. Effectively, if heat is considered to be totally storable, then CHP plant is free to operate anywhere in the merit order, subject only to the requirement that during the year sufficient heat be produced to meet demand (hence the requirement for eleven, not twelve, exogenously specified constraints). No storage process need be specified.

If ITOC (variable heat to power ratio) plant is specified, then the requirement for exogenously specified constraints multiplies as does the number of possible scenarios that can be investigated thereby.

7.4.3 Seasonal heat storage

For the purposes of the research described in this thesis, it was decided to investigate a 'middle of the road' scenario. In this scenario, four time flagged types of heat are described, implying that heat produced in one season (consisting of 3 time periods) may be consumed in any time period within that season but not within any other season. It was further specified that within any given season the CHP plant would be operated at a constant level. (This would have the effect of maximising plant efficiency). This is represented in matrix form as shown in table 7.18. In order to minimise the numbers of rows and columns the particular CHP technology was specified as required in the four CHP columns, rather than as before in the pilot study. The attribution of time periods to heat demand is specified in Appendix 8.

7.5 SUMMARY

In this Chapter a procedure for modelling the UK's electricity production processes has been described. This separate treatment is necessary since electricity is both a non-linear and a dynamic process.

A 1977 load duration curve has been determined as a basis for comparison with those calculated under different assumptions about energy technologies. The merit order is modelled by ranking plant according to its achieved load factor and is then grouped by matching output to the load duration curve. Five groups of plant are defined in this way, each supplying electricity in one of five load bands. The inputs to electricity supplied in each load band are determined from plant performance data.

Time variation is modelled by defining 12 characteristic time periods, each of 730 hours duration and determining load levels for each. The work of Baker and Mellish is used to determine the characteristic times and dates of the characteristic time periods. The load duration curve is used to determine the load level during the time period. This model of electricity production and a corresponding model of CHP production is incorporated into the A - B matrix and the marginal source of electricity can be determined by trial and error for each time period.

	electricity transmission process												CHP process				conventional heating				heat transm'n			
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	1	2	3	4	1	2	3	4
electricity t_1	1												1											
t_2		1											1											
t_3			1										1											
t_4				1										1										
t_5					1									1										
t_6						1								1										
t_7							1								1									
t_8								1							1									
t_9									1						1									
t_{10}										1						1								
t_{11}											1					1								
t_{12}												1				1								
generated heat t_1 t_2 t_3													3R								-1			
generated heat t_4 t_5 t_6														3R								-1		
generated heat t_7 t_8 t_9															3R								-1	
generated heat t_{10} t_{11} t_{12}																3R								-1
trans. heat t_1 t_2 t_3																	1				1			
trans. heat t_4 t_5 t_6																		1				1		
trans. heat t_7 t_8 t_9																			1				1	
trans. heat t_{10} t_{11} t_{12}																				1				1
penetration constraint 1																					1			
2																						1		
3																							1	
4																								1

Table 7.18 Outline representation of CHP and electricity transmission

(R = heat to power ratio)

Load duration curves may be determined from the vector x which is calculated in the normal way $x = (A - B)^{-1}f$.

The full lists of process, products and data items for the full scale study are given in Appendix 9.

8 EFFECTS OF CHP USE ON ENERGY SUPPLY SCHEDULES

As described in previous chapters, part of the philosophy of the project described is that models used to investigate complex systems should be explicitly recognised as generating understanding as well as the expected numerical results. Thus this chapter, which might otherwise be entitled 'Results' presents not only the numbers generated by the study but also the interactions which are discovered between the various causes and effects.

This chapter describes the results and preliminary analysis of the full scale study, which utilises the basic matrix used for the pilot study (see Chapter 6), together with the description of the electricity production process described in Chapter 7. The resulting 112 x 112 matrix (specified in Appendix 9) is able to take account of the non-linear relationship between inputs and output of the electricity industry and the dynamic nature of this non-linearity.

8.1 SCENARIOS INVESTIGATED

The scenarios investigated in the full scale study are similar to those investigated in the pilot study (see table 6.1). An additional scenario type is included in which sufficient HOB capacity is installed to meet half the peak heat demand on the district heating system. In this scenario type, heat only boilers are only used if the heat demand exceeds half the peak heat demand. Only coal-fired heat only boilers have been considered in this type of scenario. Table 8.1 shows the full range of scenarios investigated. Again, the scenarios are chosen less for their realism than for their ability to yield information about trends and relationships.

North Sea gas available no SNG produced	North Sea gas exhausted SNG produced
Group 1: no district heating (the 'present day')	Group 2: no district heating
Group 3: 10% penetration of heat markets by district heating	
Group 5: 30% penetration of heat markets by district heating	Group 6: 30% penetration of heat markets by district heating

Table 8.1 Groups of scenarios investigated in full scale study

8.1.1 Fuel production constraints

As in the pilot study, two principal groups of scenario are studied, those in which natural gas is available, without restriction, from the North Sea and those for which no natural gas is available from the North Sea and in which the North Sea gas is totally replaced by synthetic natural gas produced from coal. A single constraint determines which of these two groups is modelled and is operated exactly as in the pilot study (see section 6.2.1). A crude oil constraint also operates as before, as does an oil refinery capacity constraint. The net effect of this constraint is that refinery operation is fixed at its 'present day' level.

8.1.2 Electricity production constraints

As described in Chapter 7, the full scale study defines 12 'time characterised' types of electricity produced by 60 different processes. 48 constraints are used to 'order' the use of groups of power stations so that high merit plant is used first in meeting the load at any particular time.

8.1.3 Low grade heat production constraints

Eight constraints are again required for the determination of penetration of district heating but in this case these eight describe the penetration of district heating at each quarter year time period into the low grade heat market. Provision of low grade heat is not specified by individual fuels; in other words the case examined is that where the market share of each fuel remains constant in the remainder of the market. The shortcomings of this assumption are discussed in Chapter 9.

8.1.4 HOB use constraints

Four constraints are used to determine the relationship between CHP and heat only boiler capacity and are used in the CHP plus HOB ('MIX') scenarios described in section 8.1 above to specify the contribution of heat only boilers to meeting peak demand on district heating. No other 'speculative programme' is investigated in this full scale study.

8.2 RESULTS

In this section the principal results will be described and underlying effects will be identified. More detailed analysis and policy implications will be discussed in Chapter 9. Comparison will be made with results obtained in the pilot study.

As remarked in Chapter 7, there was a remote possibility that the representation of the merit order in the electricity industry by the use of constraints might cause problems of oscillation. In the event, there was no tendency at all to oscillate between solutions and the model was found to converge rapidly upon a solution for x and q by appropriate use of the electricity constraints. In practice, only one or two attempts were required to find the appropriate merit order loading constraint set.

8.2.1 Effect of district heating use upon other fuels

From the calculations done it is possible to determine the effect of both market penetration and technology upon the total requirements for fuels and upon the activity level of the principal fuel producing processes. It is in these terms that the effects of CHP/dh use is examined.

8.2.1.1 Gas

The effects of CHP/dh use upon total requirements for fuel gas is to reduce the level of requirements for all CHP and HOB technologies. This is shown in table 8.2. Since none of the CHP technologies investigated is gas-fired, the fuel savings effects are attributable principally to the displacement of gas-fired domestic and commercial heating systems with minor contributions arising from the displacement of gas fueled electricity production by CHP-produced electricity and from the displacement of electricity from the domestic heating market. At 10% penetration of the heat market, the savings in the total requirements for gas lie between 4 and 4.4%, although the output of the North Sea is reduced by between 4.2 and 4.6%, the very slight difference being attributable to the North Sea not being the sole source of gas, other gas being available both from coke production and from oil refining. Corresponding figures for 30% penetration lie around 12% with the exception of technology 4 where over production of electricity by CHP plant occurs. This is discussed in section 8.2.3.2 below. The HOB technologies show slightly reduced saving in gas requirements but it is noteworthy that even the gas fired HOB technology shows a gas saving since commercial and domestic heating plant is replaced by more efficient HOB plant. This effect is of sufficient magnitude to yield savings even though gas (through HOBs) has a larger overall market share than before. This conclusion is sensitive to changed specification of the efficiency of the processes. The MIX technologies show a slightly modified effect but nonetheless reflect the general appearance of greater sensitivity to market penetration than to technology. That there is not a greater difference between the 'straight' technologies and the MIX technologies is a reflection of the reduction in gas demand being primarily attributable to displacement of gas from the domestic and commercial heating markets. The findings in

Technology	district heating heat market penetration (%)	Total UK gas requirement (Mtherms)	Change in UK gas requirement (%)
1 oil fired CHP R = 4	10 30	16176 14765 (14810)	-4.02 -12.44 (-12.12)
2 coal fired CHP R = 2.4 η = 85%	10 30	16164 14757 (14767)	-4.08 -12.39 (-12.38)
3 coal fired CHP R = 2.4 η = 80%	10 30	16164 14757 (14767	-4.08 -12.39 (-12.38)
4 coal fired CHP R = 1 η = 56%	10 25	16116 14986	-4.37 -11.08
5 nuclear CHP R = 2.4	10 30	16164 14754 (14764)	-4.09 -12.46 (-12.39)
6 nuclear CHP R = 2.2	10 30	16161 14743 (14753)	-4.11 -12.52 (-12.46)
9 gas fired HOB	10 30	16330 15281 (15291)	-3.10 -9.33 (-9.27)
10 coal fired HOB	10 30	16194 14872 (14882)	-3.91 -11.75 (-11.69)
11 oil fired HOB	10 30	16194 14835 (14882)	-3.91 -11.97 (-11.69)

Table 8.2 Change in UK gas requirements
(R = heat to power ratio, η = overall efficiency)

(Figures in brackets refer to scenarios in which gas is available only as SNG) respect of gas requirements are similar to those determined in the pilot study (q.v.)

8.2.1.2 Coke

Coke is perhaps the simplest fuel to examine in this context since it is an input to neither electricity production nor CHP production. Any change in the total requirements for coke will be attributable solely to its displacement from the low grade heating markets. Total requirements are found to be reduced by 3.2% and 9.7% for 10% and 30% penetration of the heat market by CHP/dh; independent of CHP/dh technology. The activity level of coke production is similarly reduced.

8.2.1.3 Coal

Since coal is an input to some of the CHP/dh technologies examined, the changes in total requirements depend on a number of different influences, some of which are represented in figure 8.1. Figure 8.1 is not able to represent either the time dependency nor the load dependency of the interactions.

The calculated results presented in table 8.3 show that the total requirement for coal depends upon both the CHP/dh scenario and upon the penetration of district heating into the low grade heat markets. This arises on the CHP side because for some technologies coal is an input, on the heat side because coal is an input to domestic and commercial heat production and more importantly to electricity which is also used by the heat markets. On the electricity side the dependency occurs because coal is a major input to conventional electricity production. Because of the interactions of all these effects it is useful to examine the total coal requirement for each technology.

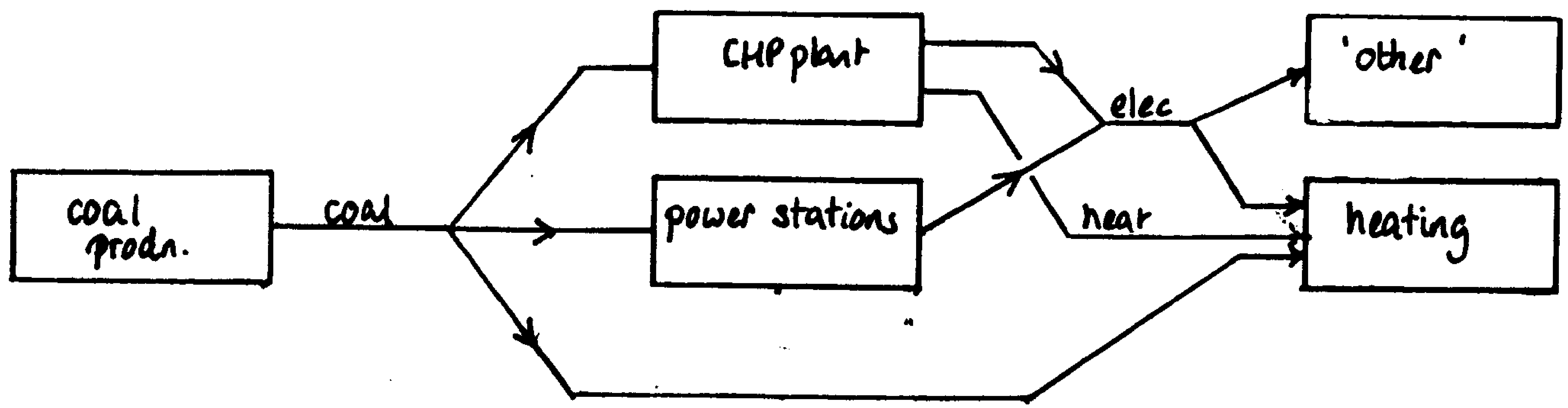

Figure 8.1 Coal/electricity/low grade heat interactions

Technology	district heating heat market penetration (%)	Total UK coal requirement (mtonnes)	Change in UK coal requirement (%)
1 oil fired CHP R = 4	10 30	118.2 105.0 (189.3)	-5.1 -15.7 (52.0) (-14.3*)
2 coal fired CHP R = 2.4 η = 85%	10 30	124.0 122.7 (206.4)	-0.4 -1.4 (65.8) (-6.6*)
3 coal fired CHP R = 2.4 η = 80%	10 30	124.6 124.5 (208.2)	+0.1 0 (67.2) (-5.8*)
4 coal fired CHP R = 1 η = 56%	10 25	127.0 130.0	+2.0 +4.4
5 nuclear CHP R = 2.4	10 30	116.5 100.2 (183.9)	-6.4 -19.5 (47.7) (-16.8*)
6 nuclear CHP R = 2.2	10 30	116.1 99.0 (182.6)	-6.7 -20.5 (46.7) (-17.4*)
9 gas fired HOB	10 30	120.7 113.0 (200.0)	-3.1 -9.2 (60.6) (-9.5*)
10 coal fired HOB	10 30	121.2 114.5 (199.1)	-2.7 -8.0 (59.9) (-9.9*)
11 oil fired HOB	10 30	120.7 113.0 (197.4)	-3.1 -9.2 (58.6) (-10.7*)

Table 8.3 Change in UK coal requirements

(Figures in brackets refer to scenarios in which gas is available only as SNG: asterisks denote the SNG baseline)

In the case of technology 1, fuel oil is the fuel used by the CHP technology and produces a significant reduction in total coal requirements by displacing both coal and electricity from the low grade heat markets. This leads to both direct and indirect reductions in coal requirements. In addition to this, the electricity produced by the oil burning CHP plant displaces conventional electricity generating capacity which is predominantly coal fired. By contrast, technology 2, which is coal fired achieves only a small reduction in coal requirement since the CHP plant itself requires a coal input. The reduction in total coal requirement achieved may thus be interpreted as a saving achieved by the improved overall efficiency of the system. This effect is discussed more fully in Appendix 10, where the crucial relationship between technology efficiency, market share and overall efficiency is examined. Technology 3, by contrast achieves no saving of coal since the input to CHP plant is comparable to that saved by improved efficiency. The overall efficiency of technology 3 is 80% compared with 85% for technology 2. However, it should be noted that the same quantity of coal in the 'present day' case is now used more efficiently than before and is thus able to achieve a net displacement of other fuels. Technology 4 is different again, having a heat to power ratio of one compared with 2.4 for technologies 2 and 3. It has a correspondingly lower overall efficiency of 56%. In other words, technology 4 is much closer to being a conventional power station and produces substantially more electricity per unit heat produced. In the case of technology 4, the total requirement for coal is increased, as a consequence of coal fired CHP plant displacing other fuels from the heat market. The electricity production efficiency of technology 4 (28%) is broadly comparable to that of baseload coal fired power stations and slighly higher than that of middle order plant. The net effect of substituting CHP derived electricity for conventionally produced electricity will primarily be that of displacing nuclear and oil-fired electricity producers. As shown in section 8.2.3.2 below the effect of the large quantities of electricity produced by technology 4 is to place a practical limit upon the size of CHP's market share. By contrast technologies 5 and 6 save considerable quantities of coal, being nuclear powered. That they save more coal than the oil-fired plant of technology 1 is attributable to the lower heat to power ratio of the nuclear plant (2.4 and 2.2 compared with 4). This means that it displaces more coal fired electricity plant than does the oil fired CHP plant. The HOB technologies 9 to 11 demonstrate the consequences of displacing inefficient coal fired heating plant and the inefficient coal to electricity to heat conversion process with the comparatively efficient district heating boilers. The technologies in which coal fired HOBs meet half the peak district heating load show consequent reductions in coal savings. It should also be noted that in the light of this study, the pilot study is shown to over-estimate the reduction in coal consumption arising from CHP use and indeed, in the case of technologies 3 and 4, to show savings to be made where increases in coal requirements are now shown to be expected with these technologies. The reason for this discrepancy lies in the area, in the pilot study, of the assumption that all electricity displaced, either by CHP-generated electricity or from the heat markets by CHP-generated heat, is produced by coal-fired plant.

8.2.1.4 Fuel oil

Fuel oil requirements are found to be reduced in all cases except where it is an input to the CHP/dh plant. This is shown in table 8.4. Reductions in requirements are found to lie around 3.3% at 10% market penetration (5.2% for technology 4) and around 9.8% at 30% market penetration where the CHP technology is coal fired. Slight variations arise as a consequence of the different heat to power ratios of the

Technology	district heating heat market penetration (%)	Total UK coal requirement (ktonnes)	Change in UK requirement for fuel oil (%)
1 oil fired CHP R = 4	10	66305	+3.1
	30	70440 (70556)	+9.5 (+9.7)
2 coal fired CHP R = 2.4 η = 85%	10	62167	-3.3
	30	57982 (58212)	-9.8 (-9.5)
3 coal fired CHP R = 2.4 η = 80%	10	62169	-3.3
	30	57989 (58217)	-9.8 (-9.5)
4 coal fired CHP R = 1 η = 56%	10	60964	-5.2
	25	56771	-11.7
5 nuclear CHP R = 2.4	10	62144	-3.4
	30	57922 (58151)	-9.9 (-9.6)
6 nuclear CHP R = 2.2	10	62062	-3.5
	30	57714 (57936)	-10.3 (-9.9)
9 gas fired HOB	10	63035	-2.0
	30	60475 (60740)	-6.0 (-5.6)
10 coal fired HOB	10	63037	-2.0
	30	60536 (60737)	-5.9 (-5.6)
11 oil fired HOB	10	63247	-1.7
	30	61108 (61365)	-5.0 (-4.9)

Table 8.4 Change in fuel oil requirements

(Figures in brackets refer to scenarios in which gas is available only as SNG)

CHP plant which displaces various small quantities of oil fired conventional electricity generating plants. The HOBs show the effect of heat market shares and as expected, the combined HOB and CHP technologies show intermediate savings of fuel oil.

The comparatively modest savings of fuel oil disguise the potentially important effect of this saving if the marginal source of fuel oil is imports where very significant reductions are recorded as in Table 8.5.

8.2.1.5 Synthetic natural gas scenarios

The major effect upon primary fuels is, as expected, upon the demand for coal; the demand for gas and fuel oil being altered only in so far as the electricity required to produce this coal is larger with corresponding increases in the demand for inputs to electricity generation. The effect of replacing North Sea gas by synthetic natural gas is to increase the demand for coal by 77%. Savings by CHP are superimposed upon this and operate to mitigate this dramatic increase in coal demand.

8.2.2 CHP and HOB characteristics

All the scenarios investigated are based on the assumption that heat is the principal product of the CHP plant and that electricity is a by-product. This assumption arises from the speculation that in the areas supplied with district heating, takeup is total and no alternative source of low grade heat is available. The district heating plant must therefore respond to the demand for heat by consumers since they have no alternative source of supply. (Alternative assumptions are discussed in Chapter 9.) The heat supply capacity characteristics determined by the model therefore depend solely upon the size and seasonality of heat demand and upon the level

Technology	district heating heat market penetration (%)	change in imports of refined fuel oil (%)
1 oil fired CHP R = 4	10 30	+15.5 +47.6 (53.2)
2 coal fired CHP R = 2.4 η = 85%	10 30	-16.2 -47.8 (-41.4)
3 coal fired CHP R = 2.4 η = 80%	10 30	-16.2 -47.8 (-41.4)
4 coal fired CHP R = 1 η = 56%	10 25	-25.4 -57.2
5 nuclear CHP R = 2.4	10 30	-16.4 -48.3 (-41.9)
6 nuclear CHP R = 2.2	10 30	-17.0 -49.9 (-43.5)
9 gas fired HOB	10 30	-9.6 -28.9 (-22.0)
10 coal fired HOB	10 30	-9.6 -28.3 (-22.0)
11 oil fired HOB	10 30	-8.0 23.9 (17.2)

Table 8.5 Changes in imports of refined fuel oil

(Figures in brackets refer to scenarios in which gas is only available as SNG) of penetration by district heating into the national heat market. The heat characteristics are thus as shown in Table 8.6 and are independent of technology and whether or not it is heat only boilers or CHP plant which is the source of heat.

The electricity generation characteristics of the CHP plant do vary with technology, being a function of the heat to power ratio of the plant, which is assumed to be constant throughout the year. The calculations show that even with heat to power ratios as large as 2.4, and at the comparatively low market penetration of 10% of the heat market, 5% of electricity is generated, in conjunction with heat, at CHP stations. Of more significance however, is the observation that at low heat to power ratios considerable inroads into electricity production are made. (Note that the above data is the percentage of total electricity production; at particular periods of the year, the proportion is very much greater. This is examined in section 8.2.3.1 following.) It is left to following sections to show what proportion of electricity generating capability is displaced by CHP-generated electricity.

Comparison with the data generated by the pilot study shows that the linear model of electricity production leads to an underestimation of the CHP capacity required, since only the average CHP load is calculated.

8.2.3 Effect of district heating upon electricity industry

8.2.3.1 Electricity requirements

The effect of using district heating technology is to reduce the total requirement for electricity by approximately 2% (when 10% of low grade heat demand is met by district heating) and 5% (30% of low grade heat demand is met by district heating). The much smaller sensitivity to

Heat market penetration (%)	Annual heat supplied (Mtherms)	Heat supply load factor (%)	Maximum supply capability (Mtherm/annum)
10	990.4	61.75	1604
30	2971.3	61.75	4812

Table 8.6 Heat supply characteristics of CHP and HOB plant

the actual district heating technology used can be related to factors such as electricity requirement of the input fuel (see Table 8.7).

Although only slight reductions in total demand for electricity are indicated as is made clear in Table 8.8, the proportion of the total supply of electricity being produced by CHP plant may be quite large and so the reduction in the total output of conventional power plant is correspondingly significant (again, see Table 8.7).

8.2.3.2 Peak demand

The peak demand upon the power stations will be a key factor in determining the required power station capacity. As observed above, electricity production from CHP plant is determined (in the scenarios investigated) by the requirements of heat production. The stock of conventional power stations is thus the marginal source of electricity. The peak demand upon power stations is determined by aggregating the activity levels x_j of the electricity production process for each of the twelve time periods to yield twelve different demand levels; each demand level is that pertaining for a characteristic one-twelth of the year. Peak demand is simply the highest of these. The model will tend to underestimate the instantaneous peak demand since the value generated is the mean load during the time period when demand (in GWh's) is highest. Minimum demand is similarly overestimated.

Several features emerge from the peak and minimum demand data shown in Table 8.9. These are that the change in peak demand (always a reduction) which results from the use of district heating is relatively insensitive to the fuel input to the CHP or HOB plant. The reduction in peak demand which is attributable to the displacement of electricity from the low grade heat market may be inferred from the calculations for HOBs. 10% and 30% penetrations of the heat market

Technology	penetration (%)	Change in total electricity requirement (%)	Change in output from power stations (%)
1 oil fired CHP R = 4	10 30	-2.07 -6.22	-5.54 -16.62 (-15.03)
2 coal fired CHP R = 2.4 η = 85%	10 30	-1.70 -5.33	-7.52 -22.57 (-20.99)
3 coal fired CHP R = 2.4 η = 80%	10 30	-1.76 -5.30	-7.51 -22.53 (-20.96)
4 coal fired CHP R = 1 η = 56%	10 25	-1.06 -2.67	-14.78 -36.96
5 nuclear CHP R = 2.4	10 30	-1.92 -5.75	-7.67 -22.99 (-21.41)
6 nuclear CHP R = 2.2	10 30	-1.88 -5.64	-8.15 -24.46 (-22.89)
9 gas fired HOB	10 30	-2.30 -6.90	-2.30 -6.90 (-5.31)
10 coal fired HOB	10 30	-2.31 -6.93	-2.31 -6.93 (-5.34)
11 coal fired HOB	10 30	-2.30 -6.93	-2.30 -6.93 (-5.34)

Table 8.7 Change in electricity requirements

[100% = 234059.8 GWh for both electricity requirements and output from power stations: figures in brackets refer to SNG scenarios.]

Technology	heat market penetration (%)	Maximum electrical output (GW)	Annual electricity output (TWh)	Percentage contribution to electricity demand
1 oil fired CHP R = 4	10 30	1.50 4.50	8.1 24.3	3.5 11.1 (10.9)
2 coal fired CHP R = 2.4 η = 85%	10 30	2.49 7.46	13.4 40.3	5.5 18.2 (17.9)
3 coal fired CHP R = 2.4 η = 80%	10 30	2.49 7.46	13.4 40.3	5.5 18.2 (17.9)
4 coal fired CHP R = 1 η = 56%	10 25	5.93 14.83	32.1 80.2	13.9 35.2
5 nuclear CHP R = 2.4	10 30	2.49 7.46	13.4 40.3	5.9 18.3 (18.0)
6 nuclear CHP R = 2.2	10 30	2.71 8.14	14.7 44.0	6.3 19.9 (19.6)
9 gas fired HOB	10 30	1.78 (Mtherms heat) 5.34 "	- -	- -
10 coal fired HOB	10 30	1.78 " 5.34 "	- -	- -
11 oil fired HOB	10 30	1.78 " 5.34 "	- -	- -

Table 8.8 Electrical output from CHP plant

[Figures in brackets refer to proportions of total electricity generated in conjunction with heat when gas is replaced by SNG]

Table 8.9 Peak and minimum demand on power stations

Technology		Peak demand on power stations (GW)	Change in peak demand (%)	Minimum demand on power stations (GW)	Change in minimum demand (%)
1977		43.76 (44.25)	0 (1.1)	12.62 (13.11)	0 (3.88)
1	10%	41.89	-4.3	12.09	-4.2
	30%	38.15 (38.59)	-12.8 (-11.8)	10.46 (10.86)	-17.1* (-13.9)*
2	10%	40.94	-6.4	11.89	-5.8
	30%	35.29 (35.71)	-19.4 (-18.4)	8.06 (8.45)	-36.1* (-33.0)*
3	10%	40.94	-6.4	11.89	-5.8
	30%	35.29 (35.71)	-19.4 (-18.4)	8.06 (8.46)	-36.1* (-33.0)*
4	10%	37.12	-15.2	11.10	-12.0
	25%	31.35	-28.4	2.66	-78.9*
5	10%	40.90	-6.5	11.85	-6.1
	30%	35.17 (35.60)	-19.6 (-18.6)	7.95 (8.34)	-37.0* (-33.9*)
6	10%	40.67	-7.1	11.80	-6.5
	30%	34.48 (34.91)	-21.2 (-20.2)	7.37 (7.76)	-41.6* (-38.5*)
9, 10, 11	10%	43.41	-0.8	12.46	-1.3
	30%	42.70 (43.13)	-2.4 (-1.4)	12.13 (12.55)	-3.9 (-.6)
1 + HOB	10%	42.17	-3.6	11.88	-5.9
	30%	39.00	-10.8	9.66	-23.5**
2 + HOB	10%	42.65	-2.5	12.09	-4.2
	30%	40.42	-7.6	10.77	-14.7**
3 + HOB	10%	42.18	-3.6	11.89	-5.8
	30%	39.01	-10.9	9.66	-23.5**
4 + HOB	10%	40.46	-7.5	11.09	-12.12
	30%	33.85	-22.6	5.44	-56.9*
5 + HOB	10%	42.45	-3.0	11.86	-6.0
	30%	38.92	-11.1	9.59	-24.0**
6 + HOB	10%	-42.03	-4.0	11.80	-6.5
	30%	-38.58	-11.8	9.31	-26.2

* Indicates a change in the
** characteristic time period during which minimum demand occurs

[Figures in brackets refer to the corresponding SNG scenarios.]

result in 0.8% and 2.4% reductions in peak demand. The situation with CHP is complicated by the contribution which CHP plant makes to electricity demand and it is evident from Table 8.9 that the characteristic heat to power ratio has the most significant effect upon peak electricity demand. Technologies with a low heat to power ratio having the largest effect upon peak demand. The data suggests a linear relationship between the change in peak demand on the conventional power stations and the reciprocal of the heat to power ratio (figure 8.2). The peak power station demand always occurs, in the scenarios investigated, during the time period characterised by the present midwinter electricity peak.

The effect of using a district heating scenario in which half the peak demand is met by HOBs is to reduce the change in peak power station demand since less electricity is available from CHP plant to reduce the demand on power stations.

The minimum demand upon power stations shows not only variation in magnitude but variation in the time period during which minimum demand occurs. In Table 8.9 a single asterisk denotes a change in minimum demand period from that characterising a midsummer night-time to that characterising an autumn night-time. Double asterisks indicate a spring night-time. No great significance need be attached to autumn versus spring, it is more instructive to note that minimum demand becomes an interseasonal event rather than a summer event as before. The reasons for this are not hard to discover. The electricity output from CHP stations is at a minimum during the summer time periods, since heat demand on the CHP plant is also at a minimum during that period. However, with a reduced space heat component, demand for electricity does not show the same increase in the interseasonal periods. During these periods space heat demand rises and with this, the instantaneous

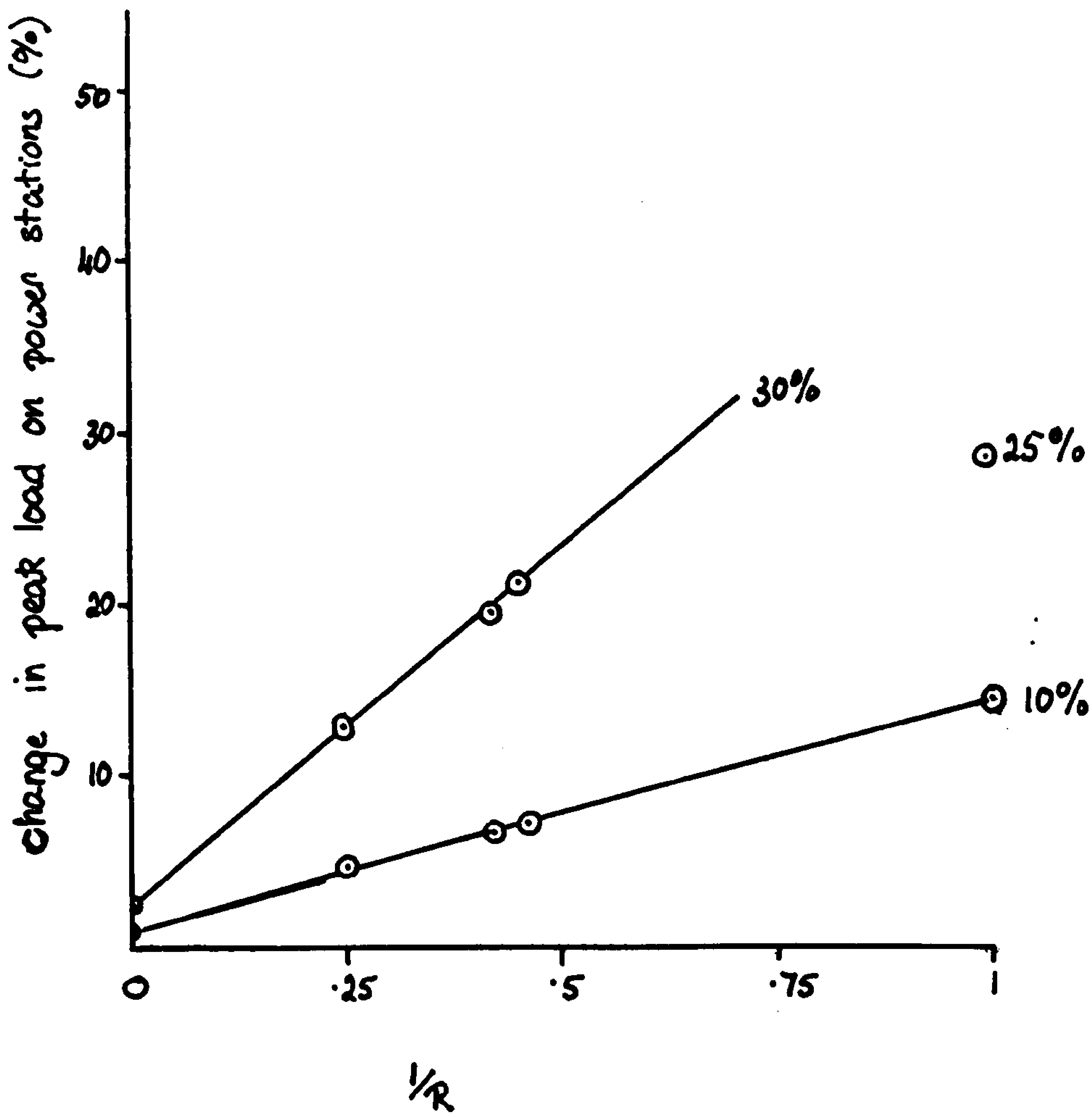

Figure 8.2 Change in peak load on power stations as a function of heat to power ratio

activity of the CHP plant increases with a corresponding increase in the availability of electricity from the CHP plant. This increase in available electricity outstrips the increase in electricity requirements, resulting in a demand upon the power stations which is even lower than that experienced during the summer. The point at which this occurs is shown as a discontinuity in figure 8.3.

It should be noted that in the case of technology 4, which has a low heat to power ratio and therefore makes a relatively large contribution to electricity supply, the decrease in peak demand is very large and the value of minimum demand approaches zero. This imposes a technical limitation upon the market penetration of this type of technology unless considerable scope for an increase in heat to power ratio is available. A 30% penetration of the heat market by technology 4 results in electricity production, by the CHP plant, in excess of the demand during that period and in the absence of the capability to store excess electricity, this represents a technically impossible scenario.

8.2.3.3 System load factor

System load factor is a measure of the utilisation of a system and as such indicates the extent to which the capital equipment of the system is able to 'earn its keep' by revenue raising production. In general the definition of system load factor, as applied to the electricity production system, measures the ratio of production to peak demand, rather than production to installed capacity.

System load factor of conventional power stations has been calculated on two bases. Firstly as the basis of total production by conventional power stations and the 1977, 'present day' peak demand and secondly on the basis of total production by conventional power stations and the peak demand upon the power stations determined for the scenario in

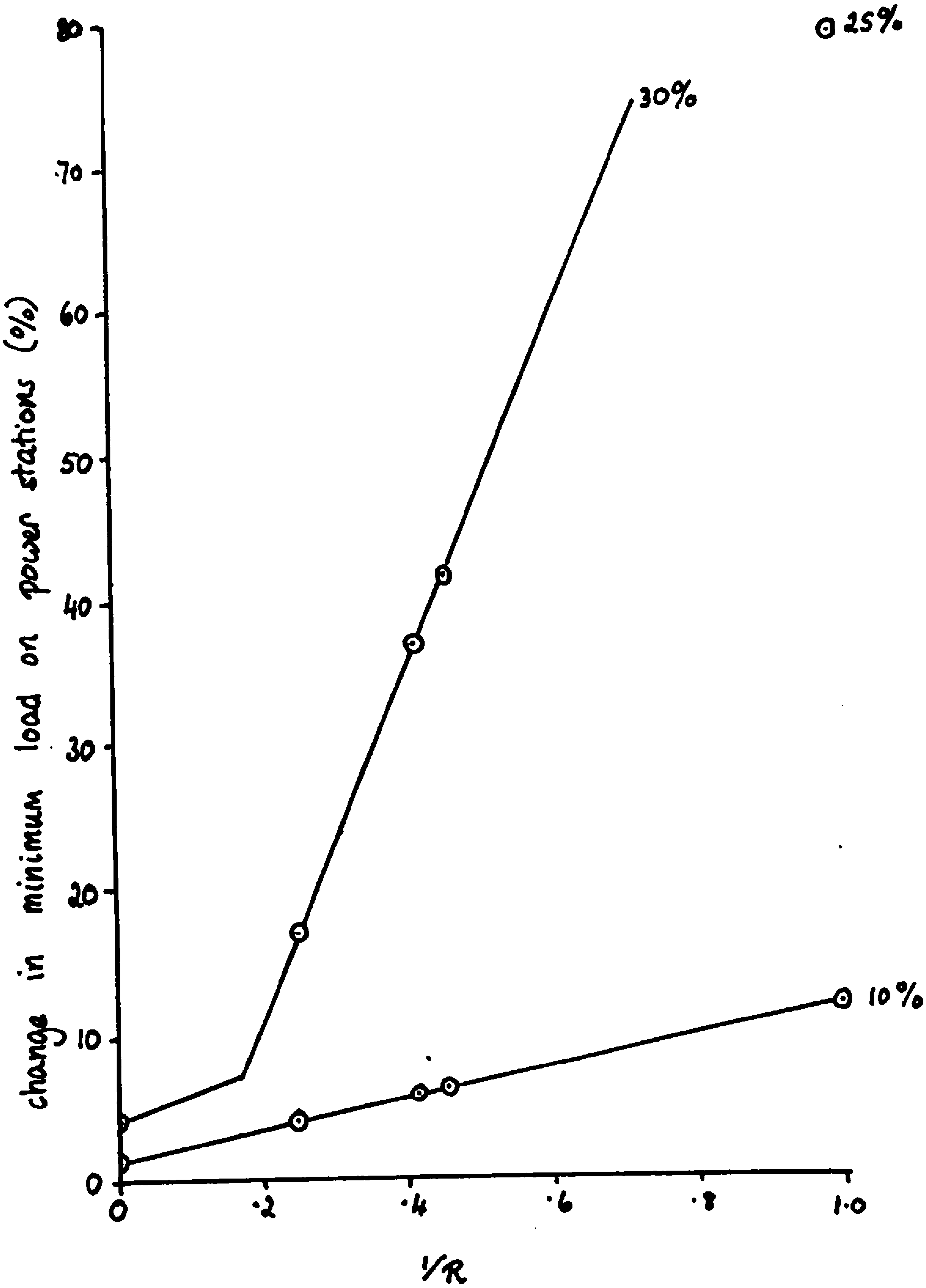

Figure 8.3 Change in minimum load on power stations as a function of heat to power ratio

question. The former is thus the system load factor if it is assumed that the stock of power stations remains as in 1977, the latter is more appropriate if a reduced capacity is envisaged with the adoption of CHP or HOB technology. These two calculations are shown in columns one and two of Table 8.10. The third column of Table 8.10 is again calculated on the basis of 1977 peak demand but includes all electricity production, whether from conventional power stations or from CHP plant. It may thus be taken as an indicator of the utilisation of the transmission system.

A number of general features emerge from the data of Table 8.10. Firstly it is evident that considerable reduction in the utilisation of the existing power station stock may occur, particularly if the CHP technology employed is one with a low heat to power ratio. This result has already been anticipated by the results of Table 8.7 where the reduction in electricity generation required from power stations was remarked.

Changes to the value of the system load factor when calculated on the basis of the prevailing peak demand are considerably less since in all cases peak demand as well as power station production is reduced. The size of the change in system load factor depends upon the relative size in the reductions in total power station electricity production and is always to reduce the system load factor, the greater reductions arising from larger heat market penetrations by district heating and from technologies with a low heat to power ratio. Reductions are approximately one percent loss in system load factor per ten percent share of the heat market for district heating. The use of heat only boilers to meet half the peak heat load on the district heating system, does not significantly mitigate the effect. In fact, the use of heat only boilers serves to reduce the system load factor since they displace

Technology		Power station system load factor (peak demand = 43.76 GW) (%)	Power station system load factor (prevailing peak demand) (%)	Load factor of total elec demand (peak demand = 43.76 GW) (%)
1977		61.058 (62.168)	61.058 (62.168)	61.058 (62.168)
1	10%	57.677	60.249	59.793
	30%	50.910 (51.879)	58.389 (58.836)	57.260 (57.707)
2	10%	56.467	60.362	59.975
	30%	47.279 (48.241)	58.634 (59.110)	57.803 (57.902)
3	10%	56.473	60.355	59.982
	30%	47.300 (48.263)	58.645 (59.121)	57.825 (57.924)
4	10%	52.036	60.716	60.409
	25%	38.493	53.726	59.425
5	10%	56.380	60.327	59.888
	30%	47.021 (47.983)	58.505 (58.983)	57.545 (57.644)
6	10%	56.081	60.345	59.910
	30%	46.123 (47.085)	58.533 (59.021)	57.610 (57.629)
9, 10, 11	10%	59.655	60.14	59.655
	30%	56.846 (57.8)	58.25 (58.6)	56.846 (57.8)
1 + HOB	10%	57.486	59.650	59.673
	30%	50.347	56.492	56.906
2 + HOB	10%	58.312	59.834	59.631
	30%	52.819	57.182	56.776
3 + HOB	10%	57.493	59.653	59.680
	30%	50.361	56.499	56.921
4 + HOB	10%	54.478	58.922	59.697
	30%	41.308	53.395	57.225
5 + HOB	10%	57.429	59.627	59.616
	30%	50.170	56.408	56.730
6 + HOB	10%	57.226	59.579	59.584
	30%	49.561	56.222	56.720

Table 8.10 Effect of district heating upon system load factor
[Figures in brackets refer to SNG scenario]

electricity from the market without contributing any electricity production capacity to reduce the net power station capacity requirement.

The system load factor for overall electricity production shows that the overall effect of CHP use is to reduce peak demand for electricity by a proportionately smaller amount than the reduction in electricity supplied. The principal reason for this is the loss of part of the demand for electricity arising from domestic hot water demand which is baseload and the loss of other trough-filling off-peak sales,both of these are major contributors to improving system load factor.

It should be noted that the values for system local factor as calculated here are somewhat overestimated. This is because the peak demand is underestimated and the minimum demand overestimated by the calculation method used (see section 8.2.3.2).

8.2.3.4 Load duration curves

The purpose and use of load duration curves is described in section 7.1.2. Data is presented in two forms in this section. Load duration curves describing power station load only are drawn and compared with the 1977 load duration curve and cumulative curves are also drawn to determine the proportion of electricity demand from the power stations which is met at various demand load factors. These are presented in Table 8.11 and in sample figures 8.4 to 8.11.

A number of general features emerge from an examination of these curves. Firstly there is a tendency to 'lumpiness' in load duration curves derived from activity level data. In part this can be attributed to the coarseness of describing annual electricity demand characteristics by

Duration band (% of year)	91.67 to 100	83.33 to 91.67	75 to 83.33	66.67 to 75	58.33 to 66.67	50 to 58.33	41.67 to 50	33.33 to 41.67	25 to 33.33	16.67 to 25	8.33 to 16.67	0 to 8.33
'Present day' (1977)	12.62	16.44	19.00	21.14	23.21	25.28	27.37	29.29	31.27	33.81	37.44	43.76 GW
Technology 1	10.46	10.76	11.03	16.65	18.50	19.86	24.00	25.40	28.20	29.08	35.25	38.15 GW
Technology 2	8.06	9.67	10.42	13.77	16.10	19.26	23.40	24.80	25.33	28.00	34.17	35.29 GW
Technology 3	8.06	9.68	10.43	13.78	16.11	19.27	23.41	24.81	25.34	28.01	34.18	35.29 GW
Technology 4*	2.66	7.43	7.78	8.81	10.06	17.60	18.16	21.74	23.25	25.18	28.12	31.35 GW
Technology 5	7.95	9.57	10.31	13.67	15.98	19.14	23.28	24.68	25.22	27.88	34.06	35.17 GW
Technology 6	7.37	9.29	10.15	12.98	15.04	18.98	23.12	24.52	24.53	27.61	33.78	34.48 GW
Technology 9	12.13	12.58	14.30	20.96	21.19	22.33	25.10	26.50	30.90	32.75	37.07	42.70 GW
Technology 10	12.12	12.57	14.29	20.95	21.19	22.33	25.09	26.49	30.89	32.74	37.07	42.69 GW
Technology 11	12.12	12.57	14.29	20.95	21.19	22.33	25.09	26.49	30.89	32.74	37.07	42.69 GW
Technology 1 + HOB	9.66	10.41	10.50	17.49	18.63	19.24	23.39	24.78	27.99	29.05	34.16	39.00 GW
Technology 2 + HOB	10.77	11.04	12.02	18.92	19.88	20.05	24.02	25.42	29.09	30.47	35.27	40.42 GW
Technology 3 + HOB	9.66	10.42	10.60	17.50	18.64	19.25	23.39	24.79	27.99	29.05	34.16	39.01 GW
Technology 4 + HOB	5.44	5.60	8.02	12.34	13.49	16.85	20.99	22.39	23.90	23.93	30.10	33.85 GW
Technology 5 + HOB	9.59	10.33	10.52	17.42	18.55	19.16	23.31	24.71	27.91	28.97	34.08	38.92 GW
Technology 6 + HOB	9.314	10.169	10.174	17.074	18.207	19.000	23.142	24.542	27.632	28.621	33.804	38.575GW

Table 8.11 Mean load in each load duration band (North Sea gas scenarios)

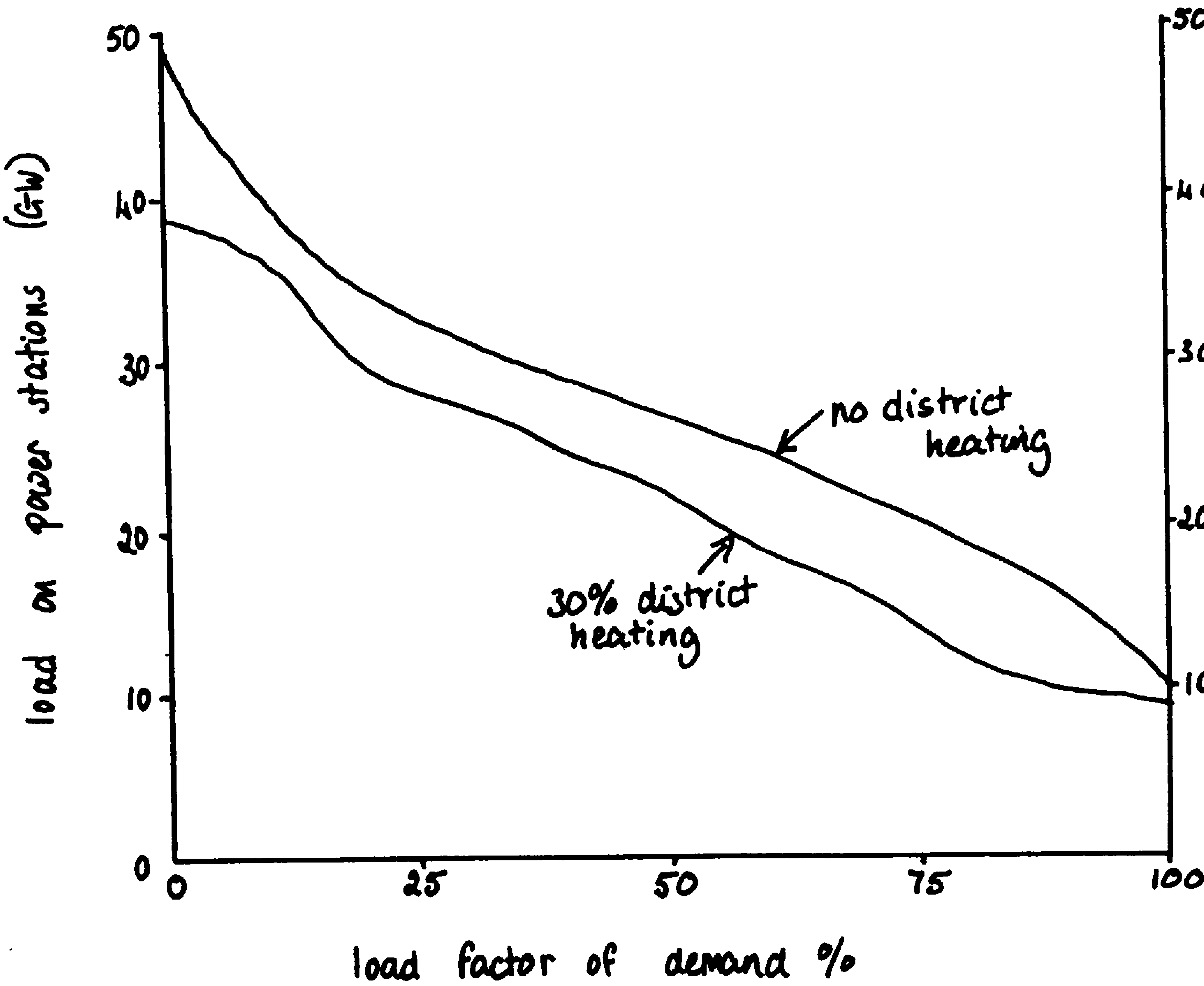

Figure 8.4 Power station load duration curve (technology 1)

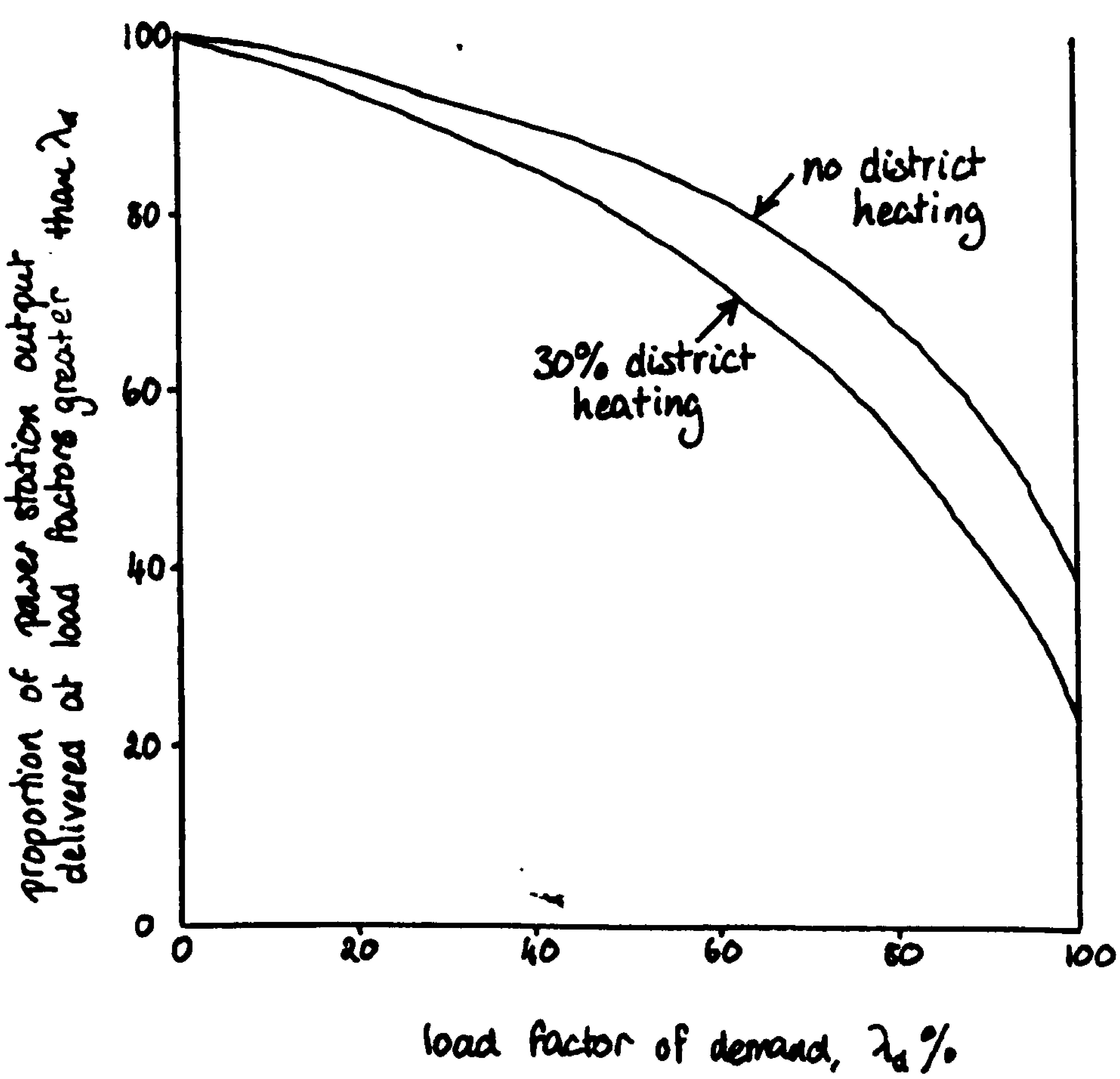

Figure 8.5 Cumulative load duration curve (technology 1)

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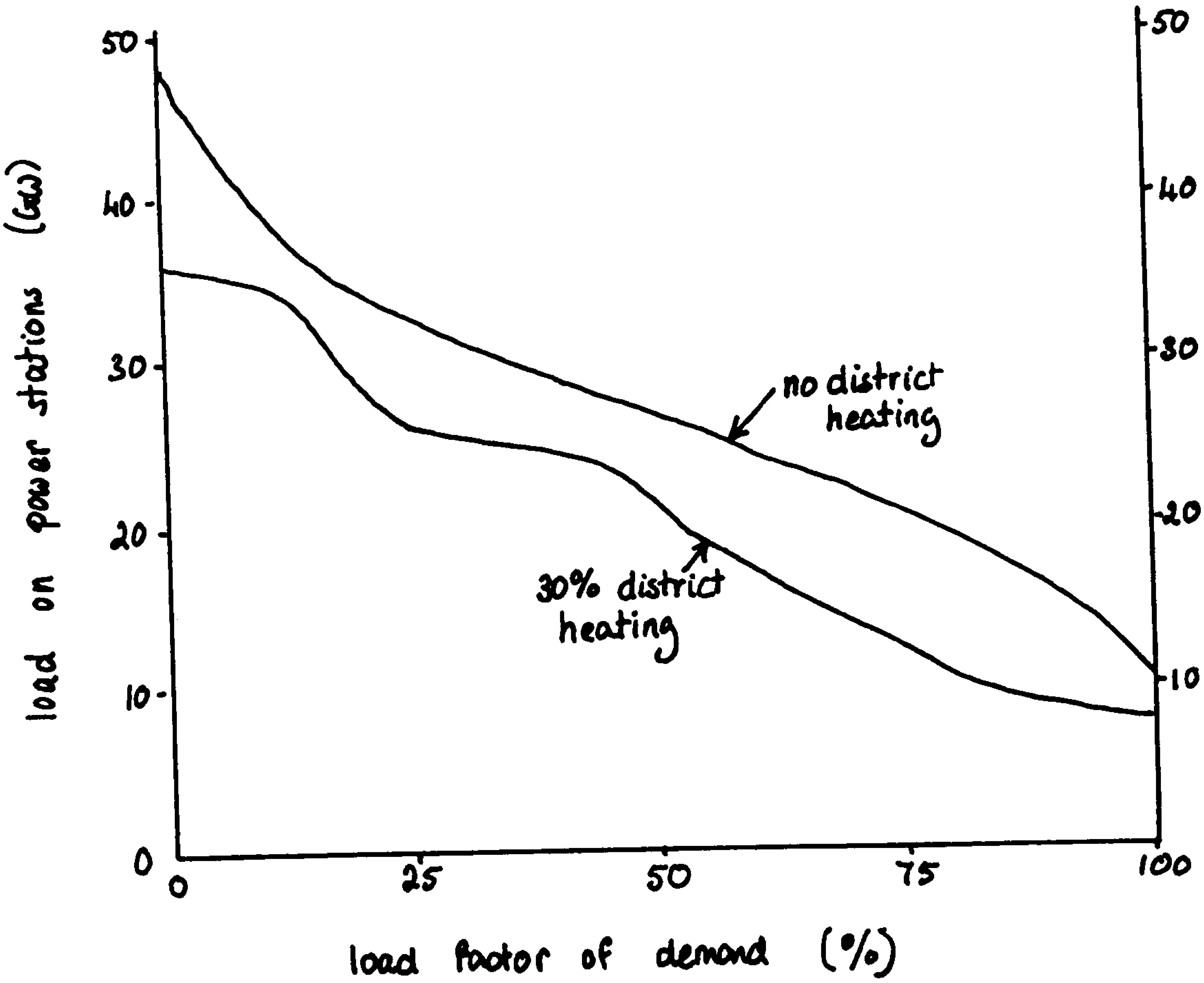

Figure 8.6 Power station load duration curve (technology 2)

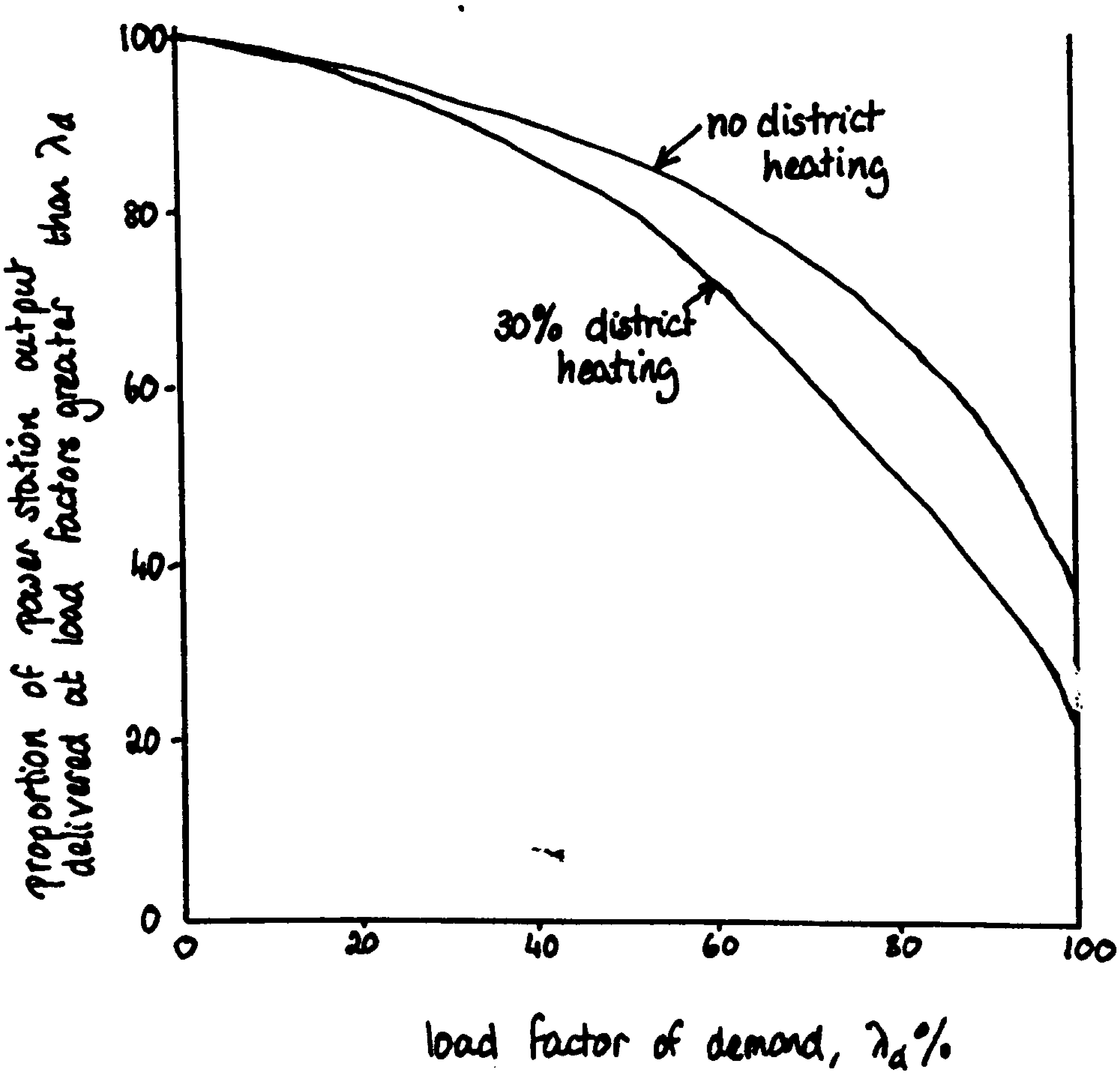

Figure 8.7 Cumulative duration curve (technology 2)

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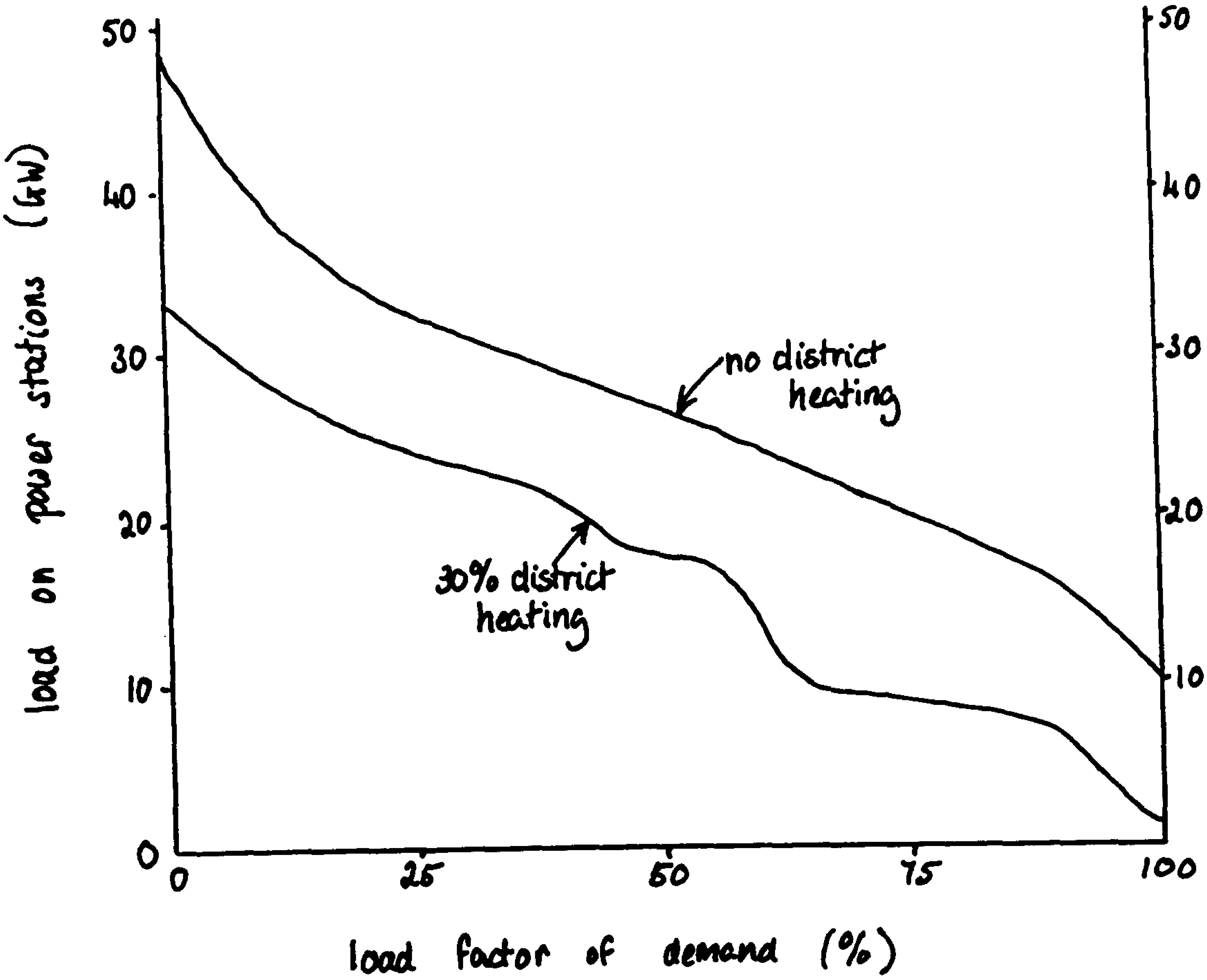


Figure 8.8 Power station load duration curve (technology 4)

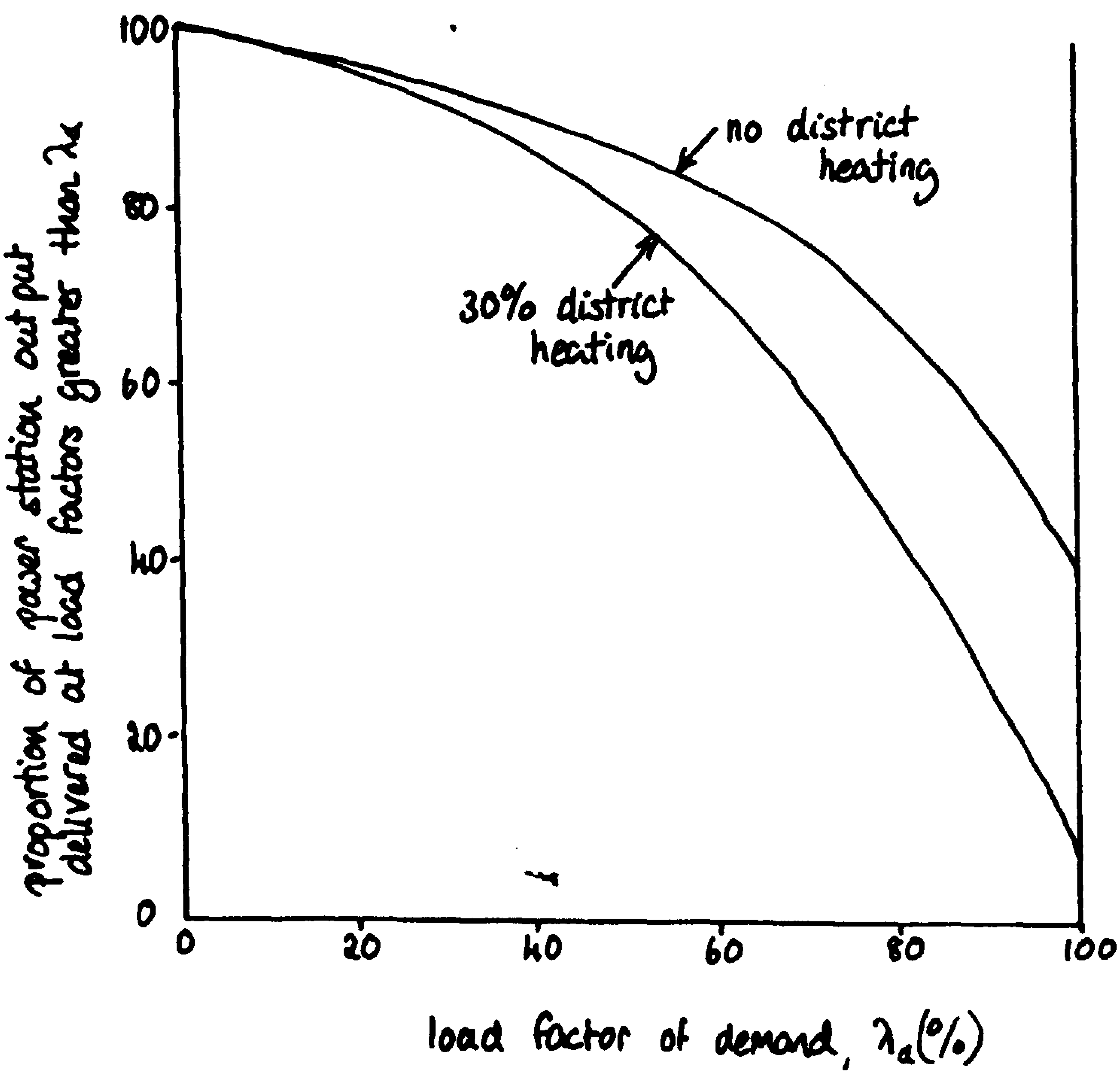


Figure 8.9 Cumulative duration curve (technology 4)

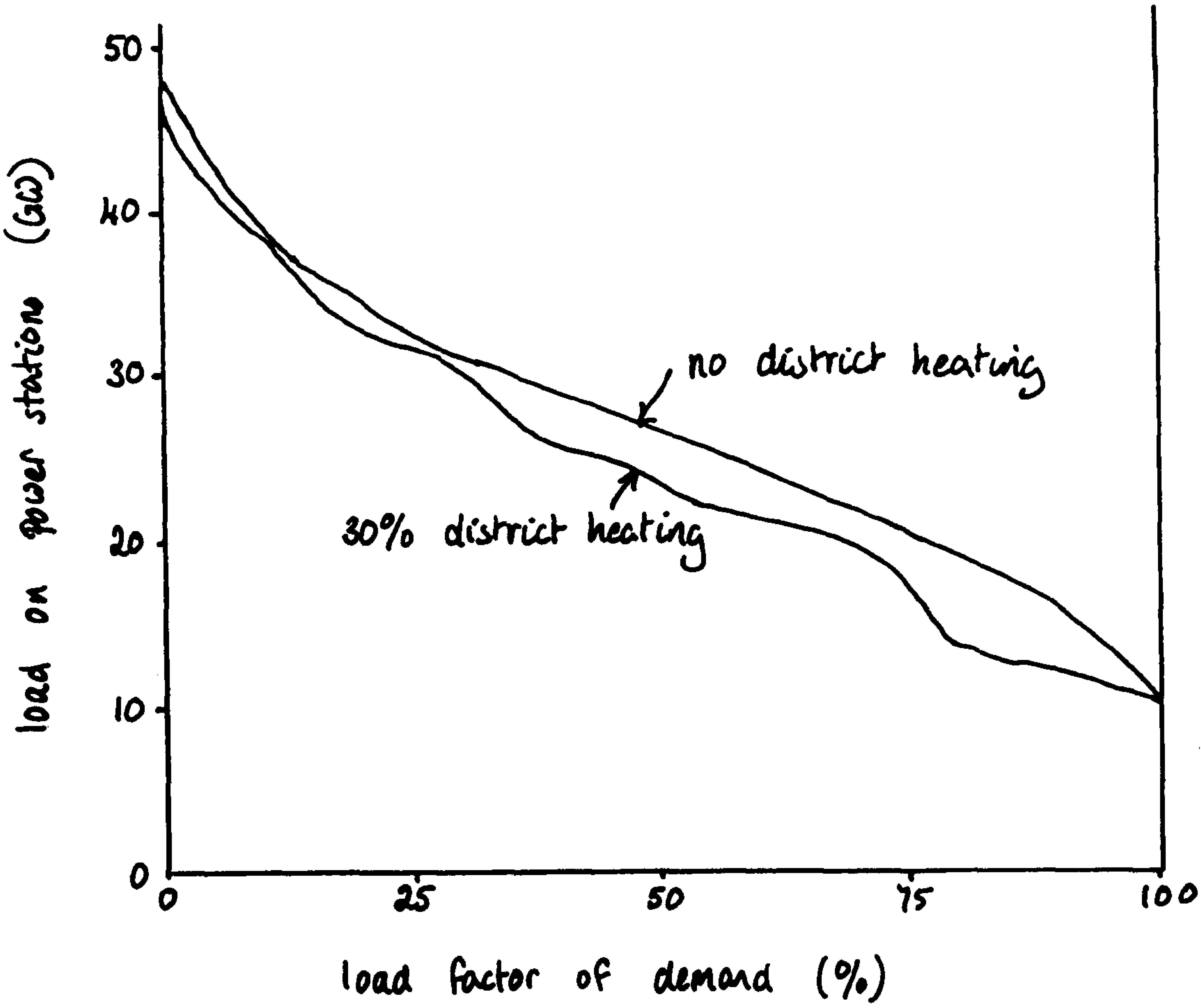


Figure 8.10 Power station load duration curve (technology 9)

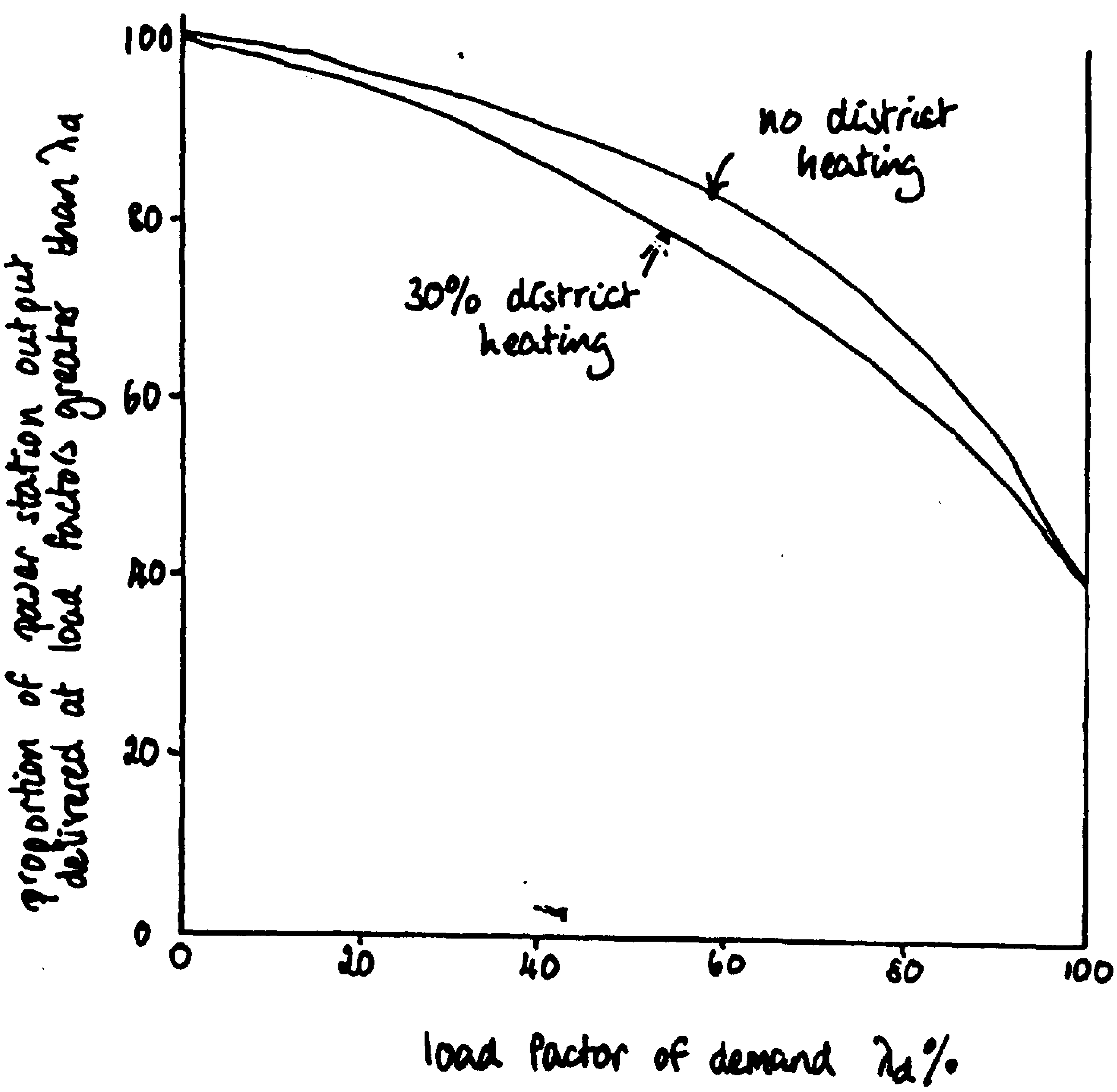


Figure 8.11 Cumulative load duration curve (technology 9)

only 12 time periods; however, real physical explanations may also be adduced and these are discussed below.

The most obvious effect of the use of either CHP or HOB district heating is that the load on the conventional power stations is reduced at all load factors of demand, which signals a poorer utilisation of the capital resources that conventional power stations represent. Taken together with the reduction in the system load factor, this implies also that even a system reduced in size, as would presumably occur as old power station plant was retired during the CHP build-up phase, would make poorer use of the installed plant. That the cumulative supply curves (figures 8.5, 8.7, 8.9 and 8.11) also exhibit a depression showing that the reduction in load exceedence is due to poorer plant utilisation than to simply a reduction in overall electricity requirements. (This might also be shown by plotting the load duration curves in the form of load divided by peak load against load factor.)

As might be expected, technology 4 with its low heat to power ratio makes the greatest inroads into the load duration curve for the conventional power stations, even though in these figures, technology 4 is illustrated with only a 25% penetration into the low grade heat market. Technology 9 with a heat to power ratio of infinity (being a heat only boiler technology) shows only a small reduction, attributable to the reduction in electricity demand for heating purposes. This curve is also indicative of the transmission load duration curves, which illustrate the total demand for electricity experienced by the transmission system and which therefore includes electricity from both conventional power stations and CHP plant. In figures 8.4, 8.6, 8.8 and 8.10 it may also be seen that whereas in 1977 86% of electricity production from power stations was supplied at demand load factors in excess of 50% for all of the technologies examined this figure had fallen to 79 ± 1%. And while, in 1977 94% of the output was delivered at load factors of better than 50%, under other technologies this proportion had dropped to between 92% (the heat only boiler technologies) and 76% (technology 4) with the remaining technologies at about 80%.

The technologies in which heat only boilers supply half the peak load show similar depressions in the load duration curve but of a lesser magnitude, for an example, see figure 8.12.

8.2.3.5 Power station activity levels

Power station activity level is the practical outcome of the features discussed in the previous section and the discussion in this section is thus closely related to that section. Activity levels for each group of power stations are recorded in Table 8.12.

In most cases the activity level of the highest stations in the merit order as represented by the Baseload I load band, is unaffected by the introduction of combined heat and power technology even when 30% of the low grade heat market is taken by district heating. The exception to this, as might be expected is that of technology 4 which, even when used in conjunction with HOBs at times of peak load, reduces the activity level of this group of conventional power stations albeit only slightly.

The picture for the Baseload II load band is rather different. This is the load band which contains power stations with net declared capabilities in excess of 1000 MW, either coal-fired or nuclear, operating with thermal efficiencies of between 32 and 35% and with station load factors of better than 64% (Appendix 6, q.v., is the source of this information). For CHP technologies with higher heat to power

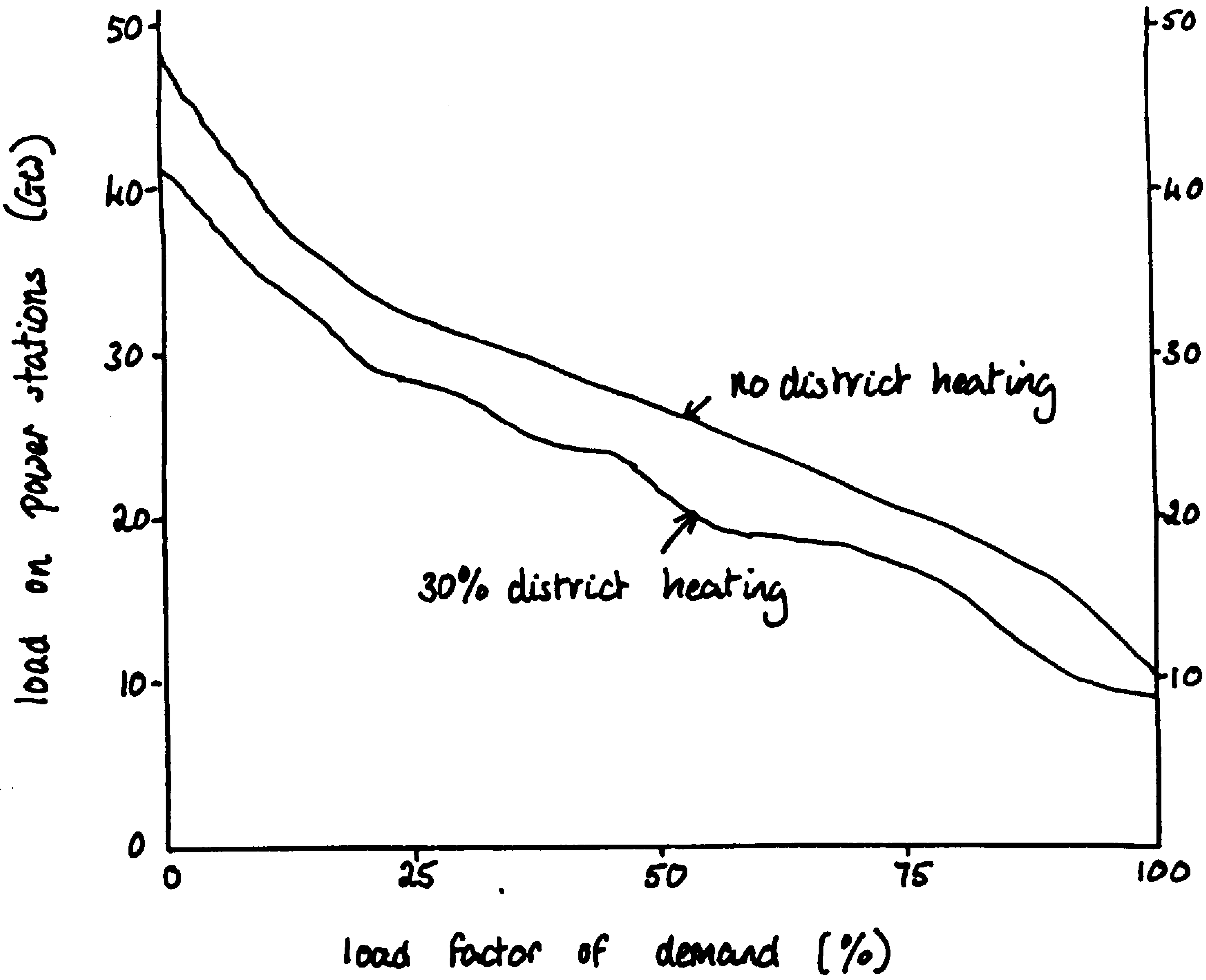


Figure 8.12 Power station load duration curve (technology 1 plus heat only boilers)

	Baseload I	Baseload II	Lowload middle	Highload middle	Peak load	
Present day	1	1	0.8614	0.4283	0.0800	
Technology 1	1	.9167	0.6210	0.2540	0.0336	
Technology 2	1	0.9496	0.6282	0.2548	0.0101	
Technology 3	1	0.9499	0.6285	0.2551	0.0102	
Technology 4	0.9556	0.7907	0.5179	0.1341	0	(25%)
Technology 5	1	0.9457	0.6251	0.2515	0.0087	
Technology 6	1	0.9284	0.6147	0.2414	0.0036	
Technology 9	1	1	0.7898	0.3570	0.0715	
Technology 10	1	1	0.7896	0.3536	0.0714	
Technology 11	1	1	0.7896	0.3536	0.0714	
Tech 1 + HOB	1	0.9894	0.6735	0.2813	0.0321	
Tech 2 + HOB	1	1	0.7154	0.3087	0.0472	
Tech 3 + HOB	1	0.9895	0.6737	0.2815	0.0322	
Tech 4 + HOB	0.9951	0.7927	0.5733	0.1626	0	
Tech 5 + HOB	1	0.9880	0.6709	0.2790	0.0312	
Tech 6 + HOB	1	0.9805	0.6624	0.2717	0.0279	

Table 8.12 Power station activity levels for each load band for 30% penetration by district heating into the low grade heat market

ratios, the reduction in the activity levels of this load band is between 5% and 7% of its 1977 level but the reduction inflicted by technology 4 is very much greater at 21%. Indeed, as can be seen clearly in figure 8.15, the activity level of the baseload II load band is reduced to the extent that it is lower than the 1977 activity level of the low load middle order load band. This may be taken as an indication that the demand met in 1977 by the baseload II load band power stations might be more effectively met by the higher load band power stations, making the baseload II power stations completely redundant. In any case, since this is the power station plant which has comparatively low unit costs, the reduction in the cost effectiveness of conventional generation system is likely to be serious unless there is radical restructuring of the stock of power stations. The use of HOBs in conjunction with CHP plant lessens the reductions in output of this band of stations to only 1 - 2% while HOBs used on their own have no effect in this load band.

The low load middle order band contains power stations with a declared net capability of between 1000 and 600 MW achieving thermal efficiencies of between 28 and 32% in the case of coal-fired plant and of approximately 35% in the case of oil fired plant. So, although not strictly baseload plant, these stations are nonetheless major contributors to the cost effectiveness of the whole system with power station load factors between 41 and 64%. Here the reduction in activity level is consistently (except for technology 4) reduced by approximately 28% in the case of CHP technologies, and 8% in the case of HOB technologies. The use of HOBs together with CHP mitigates the reduction in activity level.

Much of the plant classified as being in the high load middle order load band is of older vintage, has a lower per unit capital cost and is less

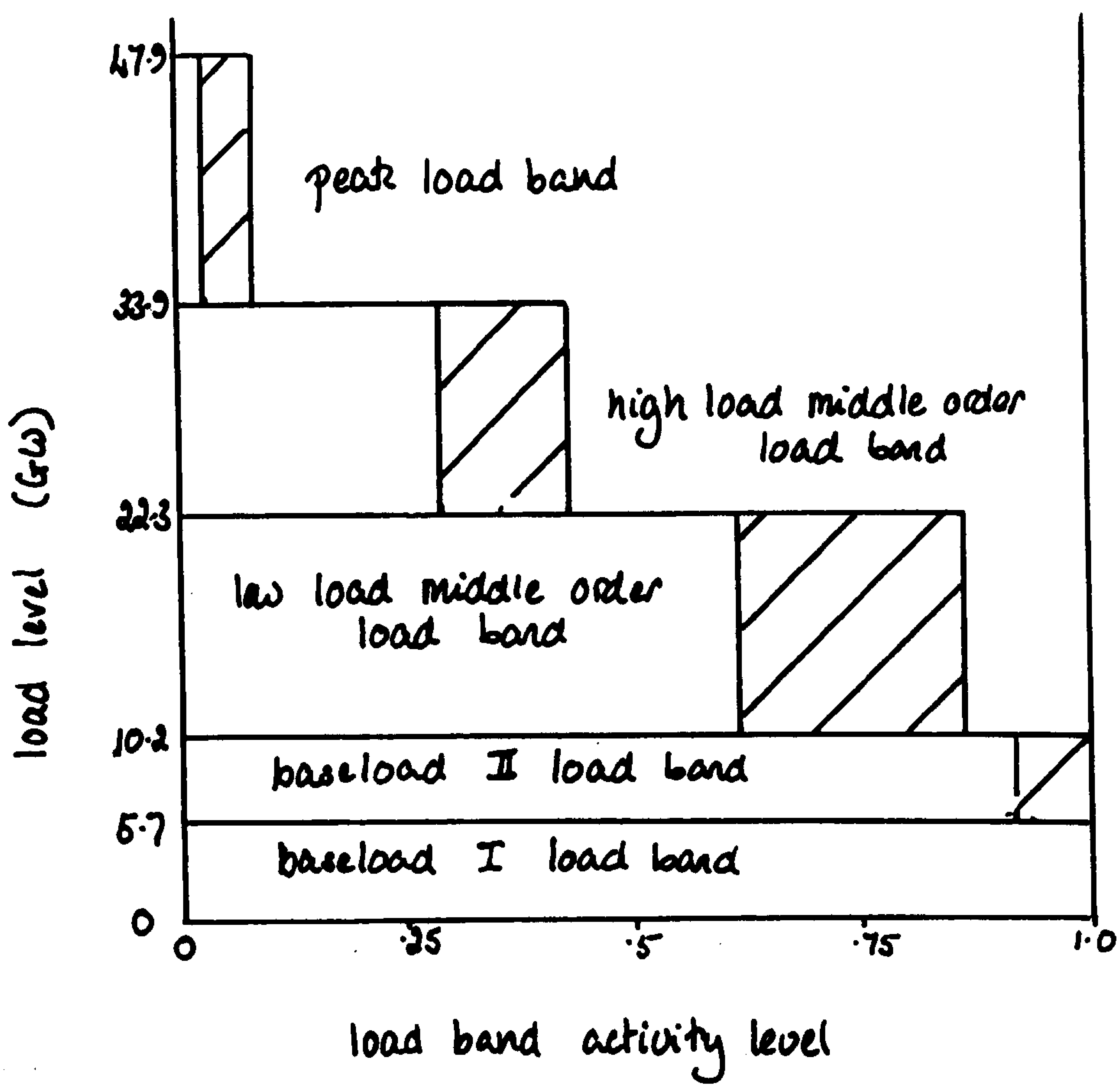


Figure 8.13 Load band activity levels of power stations operating with technology 1. CHP plant (30% penetration of heat market)

(hatched areas represent activity lost as a result of using district heating)

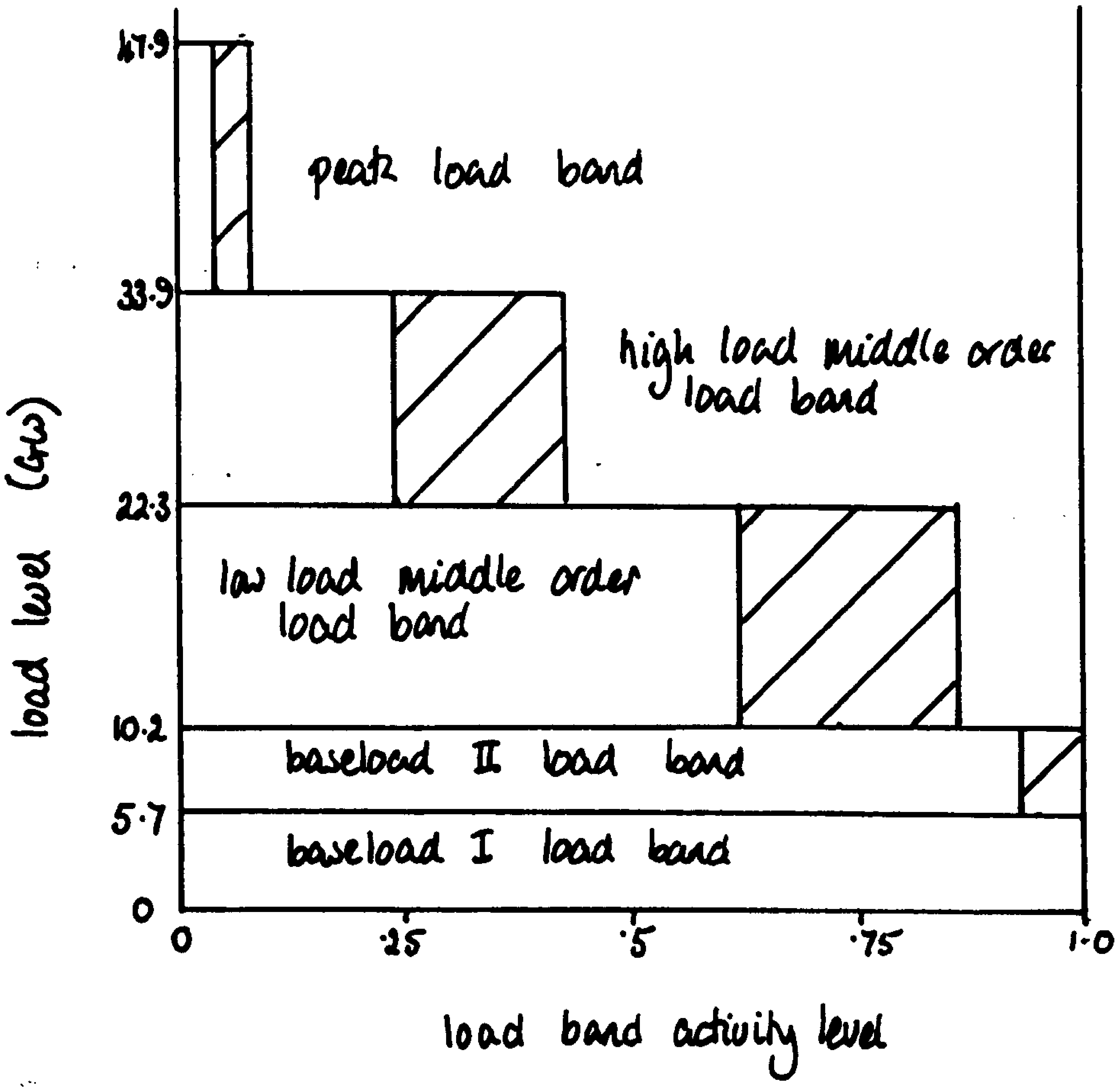


Figure 8.14 Load band activity levels of power stations operating with technology 2. CHP plant (30% penetration of heat market)

(hatched areas represent activity lost as a result of using district heating)

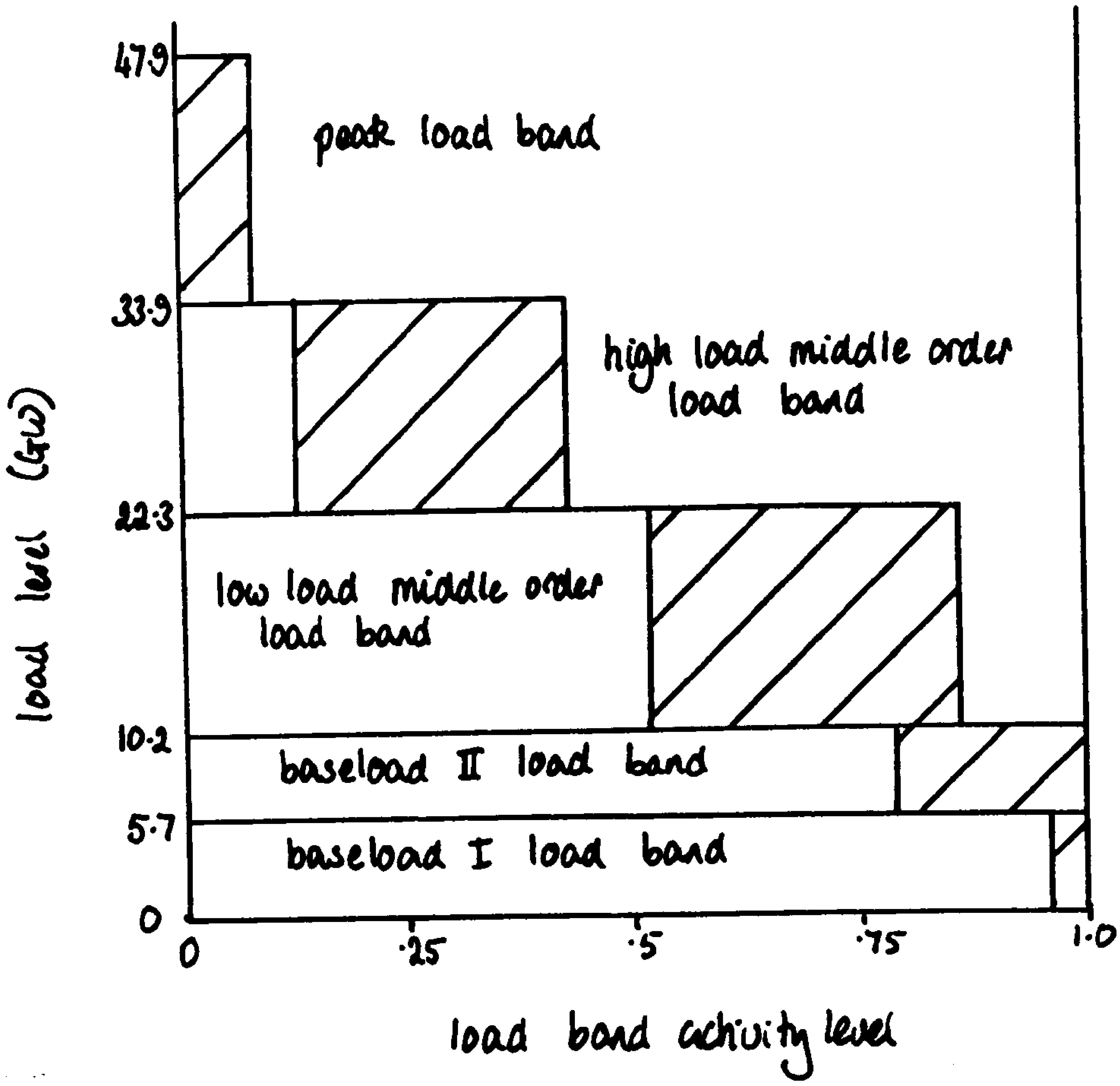


Figure 8.15 Load band activity levels of power stations operating with technology 4. CHP plant (25% penetration of heat market)

(hatched areas represent activity lost as a result of using district heating)

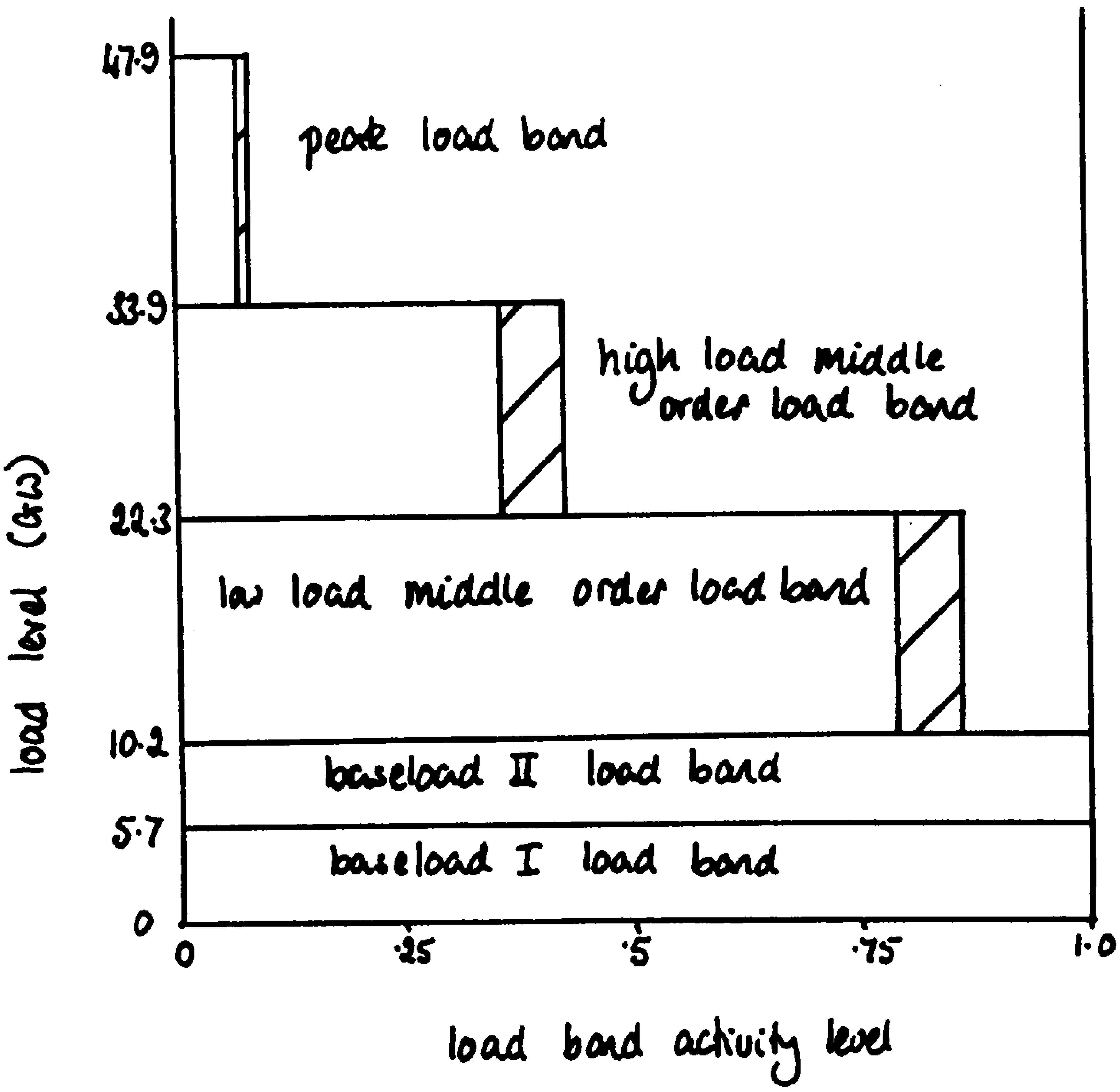


Figure 8.16 Load band activity levels of power stations operating with technology 9. HOB plant (30% penetration of heat market)

(hatched areas represent activity lost as a result of district heating) efficient. Efficiencies in this load band lie typically between 23 and 28% in the case of coal-fired plant and at approximately 30% in the case of oil-fired plant. Declared net capability in this band lies in the range 100-600 MW and stations had a plant load factor of 20-41% in 1977. The effect of a 30% penetration of district heating into the heat market is to reduce the activity level of the load band from 0.43 to approximately 0.25 for the CHP technologies; a reduction of approximately 40%. Technology 4 with its low heat to power ratio records a massive 69% reduction. With this level of reduction it is important to note that peak loads are effectively being met by plant in this load band and that therefore a major part of the electricity supplied in this load band in the case of technology 4 will be short duration peaks and that consequently start up costs and technical constraints are likely to be significant. In this case it would be unlikely that the demand could be met by plant of the type that characterises this load band; plant of the peak load band type being more appropriate. The use of heat only boilers to supply 30% of the low grade heat market with district heating leads to a 17% reduction in the activity of this load band. Heat only boilers used in conjunction with CHP plant result in a similar pattern of reductions though of lesser magnitude.

Peak load band plant consists typically of two types of plant. Gas and diesel turbines capable of rapid response to short term peaks in demand appear in this band (as in all bands) but there is also a substantial quantity of plant which is nearing the end of its life, is relatively inefficient and hence expensive to run and in extreme cases may only be operating once or twice during the year in order to 'keep it alive'. The considerable number of moribund stations that were present in the system in 1977 has since been dramatically reduced by the Electricity Supply Industry's closure programme.

The stations in this band typically have a declared net capability of less than 100 MW, a thermal efficiency of less than 23% in the case of coal fired stations and less than 30% in the case of oil fired stations and a power station load factor of less than 20% in 1977. Since this load band constitutes the marginal source of electricity only when the demand upon the power stations is high, dramatic reductions in the activity load band occur as a consequence of any technology which produces electricity.

8.2.3.6 Synthetic natural gas scenarios

The calculated results for these have already been recorded in the appropriate tables. However, it is useful to examine the change in the performance of the electricity industry which is brought about solely by the changeover from North Sea gas to synthetic natural gas. These effects are summarised in Table 8.13. The principal effect of the use of synthetic natural gas is to increase the demand for baseload electricity for use in the coal mining industry to produce the additional coal needed for gas sythesis. The slightness of this increase accounts for the broadly comparable results for North Sea gas and SNG scenarios where electricity is concerned.

8.3 ADDITIONAL RESULTS

The results presented in previous sections of this chapter contain a considerable quantity of detail. The purpose of this section is to draw some more general results from this wealth of detail and to compare these derived results with results available from elsewhere.

8.3.1 Total energy consumption

A 'baseline' criteria for assessing CHP or HOB district heating might be the effect of its use on total UK energy consumption. This can easily be determined by adding the q_i's generated for each scenario where

Total electricity requirement	238314 GWh	(+1.81%)
Peak load on power stations	44.25 GW	(+1.12%)
Minimum demand on power stations	13.11 GW	(+3.88%)
System load factor	61.47%	(+0.67%)
Activity of Baseload I power stations	1	(-)
Activity of Baseload II power stations	1	(-)
Activity of low load middle order power stations	.874	(+1.51%)
Activity of high load middle order power stations	.446	(+4.21%)
Activity of peak load power stations	.088	(+10%)

Table 8.13 Effect upon electricity industry of substituting synthetic natural gas for North Sea gas

i is either a primary energy source or an imported source of energy. Exports of primary and secondary energy are subtracted. Results of these calculations are recorded in Table 8.14. These calculations slightly underestimate the total energy consumption of the UK since they do not include nuclear electricity and hydroelectricity which cannot be determined directly from the vector q. These accounted for 3.9 and 0.6 percent respectively of UK energy consumption (8.1). Table 8.15 shows the equivalent data for the synthetic natural gas scenarios.

A surprising feature of these data is that overall, heat only boilers save greater quantities of energy than do CHP plant fuelled by coal or oil. In part, this arises because nuclear power is treated as being essentially 'free' in the accounting technique used. The implications of this result are nonetheless important because they highlight an important feature of the interaction between CHP and conventional electricity generation which this thesis has revealed. Conventional HOBs save energy when compared with fossil fuelled CHP because they replace a mixture of fuels (including electricity), inefficiently used, to raise heat. Combined heat and power plant however, also produces electricity and this displaces baseload plant from the conventional generation system. This is plant which is not only comparatively efficient but some of it is nuclear fuelled which in this accounting system is 'free'. Thus as shown in Appendix 10, there is a sense in which CHP is less efficient than equivalent conventional power generation.

Energy Paper 35 (8.2) gives a total energy saving of about 18 mtce against the existing fuel mix for 30% heat market penetration, this corresponding to 5.3%, which is broadly equivalent to that achieved by technologies 2 and 3. A slightly smaller reduction of 17 mtce is achieved against the SNG scenarios again this corresponds well to those calculated for this study.

Technology	Heat market penetration by district heating 10% Energy Consumption (mtce)	change (%)	30% Energy Consumption (mtce)	change (%)
1	331.4	-3.0%	317.4	-6.1%
2	332.6	-1.7%	320.9	-5.1%
3	332.0	-1.8%	319.2	-5.6%
4	327.2	-3.3%	(25%) 323.5	-4.3%
5	323.8	-4.3%	294.8	-12.8%
6	323.2	-4.4%	293.2	-13.3%
9	330.2	-2.4%	313.8	-7.2%
10	330.0	-2.4%	313.5	-7.3%
11	330.1	-2.4%	314.0	-7.2%
1 + HOB	331.7	-1.9%	318.6	-5.8%
2 + HOB	330.5	-2.3%	316.0	-6.6%
3 + HOB	331.3	-2.0%	317.2	-6.2%
4 + HOB	331.3	-2.0%	317.3	-6.2%
5 + HOB	325.6	-3.7%	300.5	-11.1%
6 + HOB	325.3	-3.8%	299.4	-11.5%

Table 8.14 Total UK fossil fuel primary energy requirements

Technology	Energy consumption (mtce)	Change from 1977 (%)	Change from SNG with no CHP (%)
1	347.4	2.7	-6.1
2	343.5	1.6	-7.1
3	345.3	2.1	-6.7
5	320.9	-5.1	-13.2
6	319.2	-5.6	-13.7
9	340.5	0.7	-7.9
10	339.9	0.5	-8.1
11	341.4	1.0	-7.7

Table 8.15 Total UK fossil fuel primary energy requirement for scenarios where fuel gas is only available as SNG.

8.3.2 Heat to power ratio

It has been shown in Chapter 5, and in particular in the example of technology 4 with its low heat to power ratio, that heat to power ratio is an important determinant of the effect that CHP technology has on the fuel supply schedule and in particular upon the electricity system.

In Appendix 2, it was shown that if

$$R \leqslant \frac{p}{(1 - p)Z} \qquad \text{A2.7}$$

then a CHP station could replace the 'electricity for other purposes' output of a conventional power station burning the same quantity of fuel and if

$$R \geqslant \frac{p}{1 - pZ} \qquad \text{A2.5}$$

then the electricity produced for heating purposes would also be replaced. Thus, if the condition

$$\frac{p}{(1 - p)Z} \geqslant R \geqslant \frac{p}{1 - .pZ}$$

is met then the CHP station will show energy saving advantages over the equivalent power station. This region is shown in figure A2.1 and is reproduced in figure 8.17 where the region in which CHP plant conventionally operate is also shown. This region lies between R = 1 and R = 4. The data gathered for Appendix 9 shows that for nine of the twelve characteristic time periods, CHP plant would be operating in the black zone of figure 8.17, where every unit of fuel burned in a CHP station would be capable of replacing the heat produced by using electricity from a conventional power station but no inroads into the replacement of other power plant for electricity production are made. However, for three of the time periods, indicated by lines (a), (b) and (c), the proportion of electricity generated conventionally used to provide heating is very high and in these time periods excess

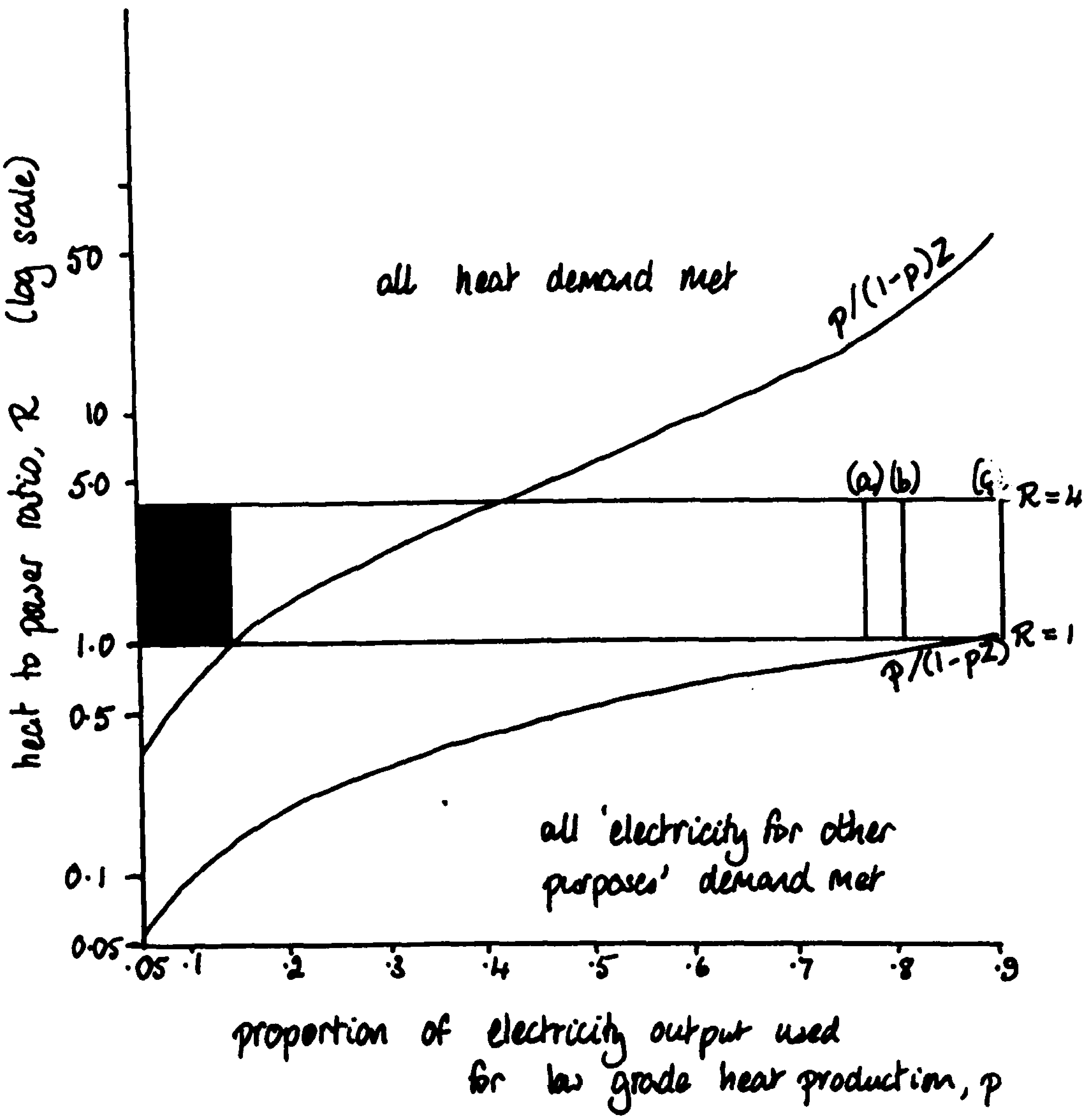


Figure 8.17 Operating region for CHP plant

electricity production occurs.

A technology by technology summary of these results is shown in Tables 8.16 and 8.17.

	Technology 1 oil fired CHP R = 4	Technology 2 coal fired CHP R = 2.4, η = 85%	Technology 3 coal fired CHP R = 2.4, η = 80%	Technology 4 coal fired CHP R = 1, η = 56% (25%)	Technology 5 nuclear CHP R = 2.4	Technology 6 nuclear CHP R = 2.4	Technology 9 gas HOBs	Technology 10 coal HOBs	Technology 11 oil HOBs
Change in gas requirements	-12.44	-12.39	-12.39	-11.08	-12.46	-12.52	-9.33	-11.75	-11.97
Change in coal requirements	-15.7	-1.4	0	+4.4	-19.5		-9.2	-8.0	-9.2
Change in fuel oil requirements	+9.5	-9.8	-9.8	-11.7	-9.9	-10.3	-6.0	-5.9	-5.0
Change in electricity requirements	-6.22	-5.33	-5.30	-2.67	-5.75	-5.64	-6.90	-6.93	-6.93
Change in power station output	-16.62	-22.57	-22.53	-36.96	-22.99	-24.46	-6.90	-6.93	-6.93
Change in peak demand	-12.8	-19.4	-19.4	-28.4	-19.6	-21.2	-2.4	-2.4	-2.4
Change in minimum demand	-17.1	-36.1	-36.1	-78.9	-37.0	-41.6	-3.9	-3.9	-3.9
Change in SLF* (power stations)	-16.62	-22.57	-22.53	-36.96	-22.99	-24.46	-6.90	-6.90	-6.90
Change in SLF* (transmission)	-6.22	-5.33	-5.29	-2.67	-5.75	-5.65	-6.90	-6.90	-6.90
Change in total fossil fuel requirements	-6.1	-5.1	-5.6	-4.3	-12.8	-13.3	-7.2	-7.3	-7.2

Table 8.16 Summary of effects of CHP/dh technologies: (North Sea gas available) (Percentage changes based on 30% heat market penetration)

*1977 peak demand

	1977 Technology	Technology 1 oil fired CHP R = 4	Technology 2 coal fired CHP R = 2.4, η = 85%	Technology 3 coal fired CHP R = 2.4, η = 80%	Technology 5 nuclear CHP R = 2.4	Technology 6 nuclear CHP R = 2.2	Technology 9 coal HOBs	Technology 10 coal HOBs	Technology 11 oil HOBs
Change in gas requirements	0	-12.12	-12.38	-12.38	-12.39	-12.46	-9.27	-11.69	-11.69
Change in coal requirements		52.0	65.8	67.2	47.7	46.7	60.6	59.9	58.6
Change in oil requirements		9.7	-9.5	-9.5	-9.6	-9.9	-5.9	-5.6	-4.9
Change in power station output		-15.03	-20.99	-20.96	-24.41	-22.89	-5.31	-5.34	-5.4
Change in peak demand	1.1	-11.8	-18.4	-18.4	-18.6	-20.2	-1.4	-1.4	-1.4
Change in minimum demand	3.88	-13.9	-33.0	-33.0	-33.9	-38.5	-0.6	-0.6	-0.6
Change in SLF* (power station)	1.8	-15.0	-21.10	-21.0	-21.4	-22.9	-5.3	-5.3	-5.3
Change in SLF* (transmission)	1.8	-5.5	-5.2	-5.1	-5.6	-5.6	-5.3	-5.3	-5.3
Change in total fossil fuel requirements	2.8	2.7	1.6	2.1	-5.1	-5.6	0.7	0.5	0.1

*1977 peak demand

Table 8.17 Summary of effects of CHP/dh technologies: (SNG scenarios)
(Percentage changes based on 30% heat market penetration)

9 FURTHER STUDY AND FUTURE DEVELOPMENTS

One of the exciting, though frustrating features of a wide-ranging research project such as that described, is the constant need to contain the urge to explore all the avenues which present themselves. This is necessary in order to retain the coherence of the project and to keep the scope of the task within achievable bounds. This chapter attempts to assemble and order some of the possibilities for further development of the project.

Further study possibilities seem to fall into two categories; that of improvements to the existing model on one hand and the development of new capabilities on the other. These two categories are discussed separately below.

9.1 ENHANCEMENT OF EXISTING MODEL

There is some scope for enhancing the quality and accuracy of the information presently contained within the matrix description.

9.1.1 Further disaggregation

Further disaggregation serves no useful purpose unless it involves the specification of a new process or product which is of interest. In particular there is no particular merit in disaggregating two or more processes for the production of one product unless some particular specification of their interrelation is also to be used. This particularly applies to the use of the degenerate assumption of 'retaining present relative importance' specified by the use of the constraint $a_{cj} + a_{ck} = 0$ (see section 4.4.1).

The most useful disaggregations are those which allow the identification of a previously unidentified dependency loop. For example, the decision not to specify nuclear fuel as an input to nuclear fuel plant might be reviewed in the light of the high electricity input required to produce the fuel. The aggregation of ore production and importing with iron and steel production and the aggregation of aluminium smelting with 'other production' are also candidates for review for this reason.

Other disaggregation will depend upon what future investigations are undertaken. Examples might include construction processes and materials of various sorts (see section 9.3.1.3 below), primary resources etc.

9.1.2 Treatment of the electricity industry

In the absence of better data, there would be little point in detailing further the electricity generation process in terms of either its dynamic aspect or its non linearity. However, the implications of assuming the integration of non-integrated electricity generating systems has not been fully investigated and it is possible that better quality information could be derived if the Scottish Boards' operations were not treated as integral with those of the CEGB.

It would also be useful to examine in greater detail the relationships between power station load factor and instantaneous load for power stations with low load factor. Although of less immediate interest, the accumulation of a large number of these stations at the bottom of the merit order and their identification, in this study, with peak load plant is not wholly satisfactory. A simple procedure which would go a long way to meeting this need would be to draw up a simple division between older inefficient plant and purpose built low load factor plant.

9.1.3 Electricity demand data

Comparatively little information is available about the breakdown of electricity demand during particular time periods. The data used in this study is primarily inferential. Although the data inferred is consistent with that available, it would nonetheless be useful to improve the quality of this data. No strategies for achieving this objective are immediately apparent while the Electricity Supply Industry retains its present reticence.

Since the results of this study show a very strong effect upon system load factor of the use of district heating plant, it is important to determine the extent to which the procedures for modelling the magnitude of electricity demand influence this conclusion. This is particularly important since much of the electricity demand data is inferential. A set of sensitivity tests to determine this might be done in a number of different ways. A number of different data sets could be generated, which fulfil the criteria established in section 7.3.3, in order to model demand level during appropriate twelfths of the year. Alternatively unequal periods of the year might be selected to represent loads in different periods of the year; this approach would enable peak and minimum demand levels to be modelled more explicitly as being of short duration. The use of more than twelve time periods to represent demand throughout the year is likely to run into the practical problem of data credibility outlined in section 7.3.3(p.200). However, a third possible approach will determine whether the coarseness of electricity demand representation is a major determinant of the calculated results. This could be done by choosing a smaller number of characteristic time periods (8 might provide an appropriate test) and repeating a typical set of scenario calculations.

Testing the sensitivity of results to the allocation of levels of electricity demand for heating to each time period may be done by allocating different data sets to each time period separately from, and perhaps subsequently in conjunction with, the sensitivity tests described for total electricity demand.

It would also be appropriate to test the implications of operating CHP plant as if it were a regular member of the merit order, only being used when electricity demand reaches a specified level. In this type of scenario heat would be a by-product of the CHP plant, supplemented by HOB plant or by appropriate use of storage.

It would be possible to use this type of scenario in the existing model by simply specifying 4 additional heat only boiler processes.

9.2 VARIABLE HEAT TO POWER RATIO

Although investigation of the impact of variable heat to power ratio would constitute a substantial new piece of work, the experience of this project shows that this would be of very great interest. This was highlighted by the example of technology 4 where the continued use of a low heat to power ratio at times of low electricity demand results in the displacement of efficient conventional electricity generation.

Although the full implications of the use of variable heat to power ratios could only be indicated by explicit treatment, as indicated below, it would be possible to gain some indication of the consequences of variable heat to power ratio by using a different value of R for each of the four seasonal CHP 'processes' used to model heat production. It should be noted, however, that the use of a variable heat to power ratio implies that regimes for determining its level must be explicitly specified. In the light of the results obtained in the present study, the use of appropriate variations of R in order to maximise (or at least, minimise the reduction in) the SLF of the conventional power station stock would be an appropriate starting scenario.

Two types of scenario suggest themselves for examination and these are discussed below.

9.2.1 Constant electricity output

It would be possible to investigate the implications of using CHP plant to supply electricity continuously and to vary the heat to power ratio so as to provide a varying heat output. If heat demand varies between h_{min} and h_{max} then the constant electricity output e is given by

$$e = \frac{h_{max}}{R_{hmax}} = \frac{h_{min}}{R_{hmin}} \quad . \tag{9.1}$$

where R_{hmin} and R_{hmax} are the values of the heat to power ratio, R, when h is a minimum and a maximum respectively. If the technology is capable of operating between limits of R_{min} and R_{max}, then clearly

$$R_{max} \geqslant R \geqslant R_{min} \tag{9.2}$$

which means that

$$R_{max} \geqslant R_{hmax} \geqslant R_{hmin} \geqslant R_{min}$$

$$R_{max} \geqslant \frac{hmax}{e} \geqslant \frac{hmin}{e} \geqslant R_{min} \tag{9.3}$$

Taking the first pair of inequalities

$$R_{max} \geqslant \frac{hmax}{e}$$

$$\therefore \quad e \geqslant \frac{hmax}{Rmax} \tag{9.4}$$

And from the second pair of inequalities

$$\frac{hmin}{e} \geqslant R_{min}$$

$$\therefore \frac{hmin}{R_{min}} \geqslant e \tag{9.5}$$

$$\therefore \frac{hmin}{R_{min}} \geqslant e \geqslant \frac{hmax}{R_{max}} \tag{9.6}$$

This can be expressed graphically by Figure 9.1 in which ABCD represents represents the possible operating region of the plant.

The operation of CHP plant with variable heat to power ratio can be represented in a matrix model by the use of dummy processes and products. In the example of Table 9.1, fuel is fed into CHP plant, represented by two processes j = 2 and j = 3. Each represents the two extremes of heat to power ratio. In column 2, the heat to power ratio is one and in column 3, the heat to power ratio is 4. The two products are dummy electricity and dummy heat. Each dummy product acts as an input to a single process which produces either heat or electricity. The CHP production process can thus be seen as the weighted sum of the two processes for which there is an associated 'assembling' process. The heat to power ratio of the CHP process is

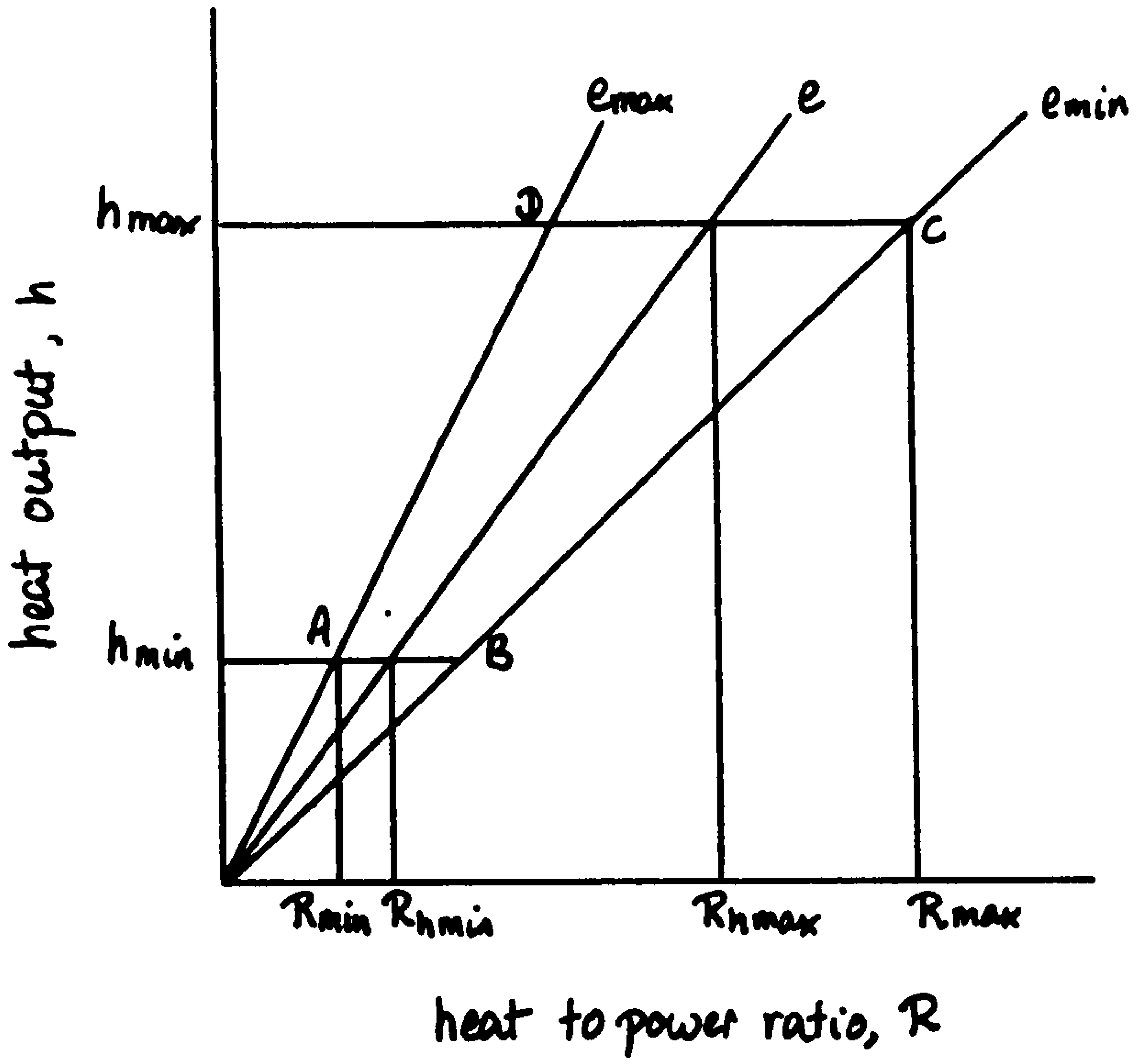


Figure 9.1 Output mix and heat to power ratio (constant e)

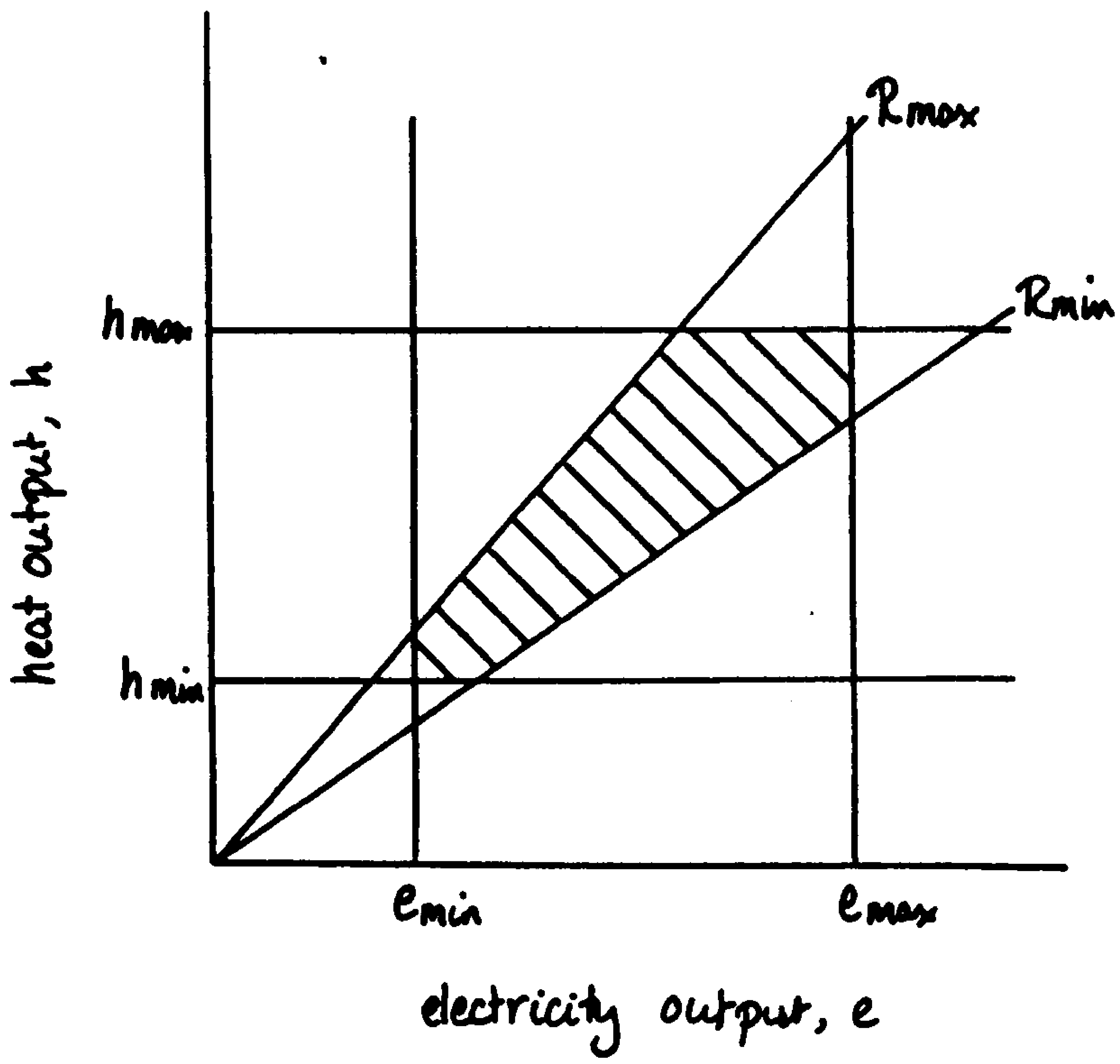


Figure 9.2 Operating region for variable heat to power ratio plant

	fuel production	CHP, R = 1	CHP, R = 4	electricity summing process	heat summing process	conventional heating	demand
fuel	100	-70	-130	-	-	-120	200
dummy electricity	-	20	20	-20	-	-	0
dummy heat	-	20	80	-	-100	-	0
electricity	-	-	-	20	-	-	20
heat	-	-	-	-	100	100	100
district heating penetration	-	-	-	-	1	-	.45
x_j	3.73	.58	.42	1	.45	.65	

Table 9.1 Matrix representation of CHP process with variable heat to power ratio (constant electricity output)

is given by

$$R = \frac{R_2 x_2 + R_3 x_3}{x_2 + x_3} \tag{9.7}$$

where $x_2 + x_3$ is a measure of the activity of the overall CHP process with respect to electricity production. The assumption that overall efficiency is linearly related to heat to power ratio is also implicit in this approach and

$$\eta = \frac{\eta_2 x_2 + \eta_2 x_3}{x_2 + x_3} \tag{9.8}$$

A negative value of x_j for the process representing R_{min} indicates that the required value of R for the overall process exceeds R_{max}. Similarly a negative value of x_j for the process representing R_{max} indicates that the required value of R is less than R_{min}.

This approach may be applied to time flagged electricity and heat, each CHP process being replaced by 4 time flagged processes. This is potentially problematic because of the considerable increase in matrix size.

9.2.2 Variable electricity output

In this case the only constraint would be that

$$R_{max} \geqslant R \geqslant R_{min} \tag{9.9}$$

shown by the hatched region in Figure 9.2. In this case additional specification in the form of constraints are required to specify what the relative outputs of heat and electricity shall be.

In the example of Table 9.2, it is specified that heat market penetration by CHP is 30%, while CHP is also to provide 40% of the electricity requirement. This is only one of a number of possible policy specifications.

	fuel production	CHP, R = 1	CHP R = 4	electricity summing process	heat summing process	conventional electricity productivity	conventional heat production	demand
fuel	100	-70	-130	-	-	-200	-120	200
dummy electricity	-	20	20	-50	-	-	-	0
dummy heat	-	20	80	-	-100	-	-	0
electricity	-	-	-	50	-	-	100	50
heat	-	-	-	-	100	50	-	100
heat production share	-	-	-	-	1	-	-	.3
electricity production share	-	-	-	1	-	-	-	.4
x_j	4.84	.833	.167	.4	.3	.6	.7	

Table 9.2 Matrix representation of CHP process with variable heat to power ratio (specified output of both heat and electricity)

9.3 FUTURE INVESTIGATION

Future investigation possibilities can be considered in two categories. There are those which would significantly enhance the understanding already gained of the implications of CHP use and those which would represent a departure into separate although related fields of study.

9.3.1 Project developments

There are those developments which can be undertaken with only minor adjustments to the matrix in order to investigate other scenarios which have a bearing on the simple CHP/dh scenarios already investigated. In particular they include investigation of some of the assumptions inher inherent in the present study. In particular the following assumption might be investigated very easily.

1 The effect of varying the ratio of imports and domestic production of iron and steel.

2 The effect of using different market penetrations for commercial and domestic district heating.

Of these two, the second is likely to have a substantially greater effect than the first. The release of the capacity constraint upon domestic oil refining is also likely to be of very minor significance.

9.3.1.1 Market share effects

A major assumption made in the scenarios studied and reported is that fuels maintain their present relative shares of the low grade heat markets. The importance of making this assumption is discussed elsewhere. However, it is clearly also necessary to be able to determine the impact of CHP/dh use in conditions where the relative shares of this market taken by each fuel is different to what it is now. In particular, many scenarios for CHP/dh implementation would include the decreased use of fuel gas due to its anticipated rising relative price over the next 20 years. It is important therefore to identify the effects of changes in market share, in order to understand which effects are attributable to market share changes and which to CHP/dh use.

This capability is easily achieved, by disaggregating the single columns of 'domestic heating' and 'commercial heating' and restoring them to the ten columns originally used in the pilot study and assigning appropriate values to the inter-relating constraints.

The all-electric economy

A market share concept about which there has been much discussion is that of the 'all-electric economy'. (See Brooks 9.3.) It would be of very great interest to determine the implications of electricity being the sole source of low grade heat both on its own account and as background technology for the introduction of CHP/dh. Further developments of this theme might be the investigation of this type of technology in conjunction with a much larger proportion of nuclear power plant; perhaps nuclear CHP plant.

Geographical bias in market share

An additional assumption implicitly used in the project is that CHP/dh will displace all fuels proportionately from the fuel market. In practice this is unlikely to be the case since there are significant differences between regions and environments in the market shares held by each fuel. Since CHP/dh is likely to be preferentially implemented in large conurbations it is likely to displace disproportionately those fuels which have larger market shares in the conurbation (eg gas). In addition, there are regional differences in fuel use, reflecting differing housing stocks, clean air regulations and tradition. The importance of these effects has yet to be investigated and it is not known how significant they are likely to be for CHP/dh studies of this sort.

Resolution of this issue could lead to a future study of the implications of energy conservation in the home by energy saving measures and shifts to more efficient home heating technologies.

9.3.1.2 Heat storage

The research carried out so far has included the assumption that half the heat demand in the peak quarter would be met by heat only boilers, that heat is produced continuously in each quarter and that heat produced during one quarter may only be used during that quarter. This embodies a complex set of assumptions about heat storage. Firstly, it assumes that the storage facilities which would enable storage of heat between quarters do not exist. However, there is an implicit assumption that there is adequate storage so that variations in the rate of demand within the quarter can be met by a constant level of heat production. A model of storage may be defined in terms of a process in which heat generated during one time period is converted into heat available at another period. Although not fully developed, this approach may be illustrated by Table 9.3 in which an example is shown. In this example, there are three time periods. Heat production by CHP plant is constrained by other processes (not shown). Twenty percent of heat in storage is an alternative process to heat transmission.

The importance of the introduction of a heat storage process is that CHP is then no longer constrained to operate to operate in accordance with the needs of heat demand. Instead, CHP processes may, for example, be allocated specific positions in the electricity production merit order producing heat as a by-product for use via buffer stores.

The introduction of a storage process will allow radically different specifications of CHP technology to be investigated, as well as

		CHP			heat storage			HOB		
		t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3	f_i
heat for storage	t_1	100				-100					0
	t_2		100				-100				0
	t_3			100	-100						0
heat for use	t_1				80			100			80
	t_2					80			100		150
	t_3						80			100	100
CHP constraint	t_1	1									.5
	t_2		1								1
	t_3			1							1
	d_j	.5	1	1	1	.5	1	0	.6	.2	

Table 9.3 Heat storage example

allowing direct determination of the storage capacity required in each case.

9.3.1.3 Equipment production

The work of Chapman and Mortimer (9.3) has shown the importance, under certain conditions, of the production inputs in producing the capital equipment for a new technology. It is not possible to determine, within the scope of the present study, how significant is the quantity of (say) energy inputs required to produce the capital equipment needed for the introduction of CHP/dh technology.

To investigate the input requirements of the technology's capital equipment, requires a dynamic aspect to the model since capital equipment produced in year zero will not itself be available for the production (or transport) of heat and/or electricity until year n where n is a positive number (the 'deployment time'). In addition the production of capital goods in year zero may require inputs not only in year zero but in years before year zero and, if the technology is either very novel or represents a major change in the production level or both, capital equipment may be required in year -m which must itself be produced in some previous year.

The conventional approach to dealing with this problem is the use of a dynamic input-output model in which the elements in the matrix X and in the final demand vector f change according to some function of time to represent improving technology and changing demand levels, often incorporating some feedback loop between the two (today's final demand includes the capital equipment for tomorrow's improved technology). This approach however requires a large predictive element: the time dependency of each element of the input-output matrix being determined by observing time trends from historical data. The inherent presumption that the future will be a continuation of past trends, limits the usefulness of the resulting model to areas where technological progress takes the form of incremental improvements in technical coefficient. The case where radical changes in technology occur are less easily modeled in this way.

An appropriate development of the present project to determine capital formation effects would be to use the matrix description on a year-by-year (or more appropriately five years by five years) basis, specifying at each time interval the capital formation required to effect the introduction of the new CHP technology. This 'step-wise dynamic' approach, while perhaps being tedious to operate, retains the advantages built into the model from the outset, notably that of transparency and maximum control by the model user. It is certainly more appropriate to use this approach where the technology involved, CHP, is more likely to appear as a consequency of deliberate centralised policy decision taking, than as a consequence of demand preferences expressed through the market. The manufacture on appropriate level of CHP capability appears as an increment in the appropriate f_i's.

The second order capital requirement effects, the 'capital to build capital' requirements, might be dealt with at each time interval by applying some maximum acceptable change on each process activity level, representing a capacity limitation. Values of x_j in excess of the maximum would require either changes in demand levels, production constraints as expressed in the A-B matrix or respecification of demand levels for previous time periods to provide the appropriate increments in capacity. This approach will require further thought and development since it is not apparent that there will be any convergence in this approach either by 'stepping-foward' from a known year or by 'stepping-back' from a required future technology state.

The current state of disaggregation of the matrix is of course quite inappropriate for the determination of capital formation effects. A new disaggregation will need to be done based on detailed inventories of capital equipment requirements. It is to be anticipated that the acquisition of such an inventory in an appropriate form and the disaggregation of the appropriate power plant, construction, building materials and civil engineering sectors will constitute a major data collection exercise which, though valuable in its own right, would be extremely time-consuming. In addition to straight forward inventory specification it will be necessary to specify manufacture and deployment times for each item of equipment.

Once a step-wise dynamic approach is adopted, it might also be possible to model the relationship between input-output ratios and capital vintage. This effect is likely to be of most significance in the case of electricity generation where older plant is noticeably less efficient than new equipment. The effect of vintage upon productivity is reviewed briefly by Stoneman (9.4). However, it is the judgement of the author that the treatment of vintage effects is likely to yield little return for expenditure of research effort and therefore probably comes under the category of 'hypercomprehensiveness' (see section 3.1.2 and Lee (references from Chapter 5; 5.3)).

It is important to note that in the area of capital formation, as in other areas, implications arising purely from economic effects cannot be modelled directly. Thus the stimulating effect of capital formation upon the rest of the economy as a result of financial investment (creating jobs (though see section 9.4), stimulating consumer demand etc.) must be specified exogenously.

The treatment of capital formation may be linked with associated economic studies of CHP introduction.

9.3.2 New studies

The matrix approach, and indeed much of the data, developed for the investigation of the effects of district heating use is likely to prove extremely useful in similar studies of related technologies. However, it should be remembered that the model itself was developed quite specifically for investigation of CHP/dh and not for universal applicability. Much of what has been learned about CHP has arisen from construction rather than operation of the model. Some of the perceived usefulness of the model might be lost if another (or, indeed this) investigator where to modify it for study of another type of technology. The author would recommend a complete stripping down of the model, to its basic equation, if any but a closely related technology were to be investigated. That said, there would be much commonality between this model and that for an investigation of energy technologies with a potentially strong interaction with electricity production. Electric heat pumps are the most obvious example; they also have strong links with heat supply. Other heat supply technologies (gas fired heat pumps, solar energy etc.) might require modification to include wider treatment of storage strategies.

The treatment in this study of electricity production, including the load duration curve and merit order features would prove useful elsewhere, particularly where predictable sources of electricity were involved. An example might be the Severn Barrage or any additional source of electricity such as additional nuclear baseload or non baseload plant. Electricity storage could be investigated using a modified version of the approach.

9.4 ECONOMIC ASPECTS

This study has been deliberately confined to the exploration of the technological impact of the operation of CHP/dh based on a number of assumptions which have a technological rigidity (for example that power stations require a certain quantity of fuel in order to produce an output). The presumption is that this technological rigidity imposes certain structures upon energy supply schedules independently of the economic environment. This is not in any way to diminish the role of economics in determining energy supply schedules but rather to explore the technological map over which economic effects will operate.

It is apparent from the present study that CHP/dh would have a significant effect upon the electricity industry as it is presently structured. It would be appropriate now to follow a related study whose aims would be to determine the following

1 The effect of CHP use upon the cost effectiveness of the electricity industry under a number of assumptions about fuel prices and the cost of electricity produced by CHP plant

2 The change in the unit cost to the consumer of electricity and the cost of CHP/dh heating

3 The effect of changing prices upon the market share of each fuel

4 An appropriate capital plant structure towards which the electricity industry might evolve in order to minimise the potential reduction in its cost effectiveness that would be caused by CHP/dh.

In all of the above, the output from this study would be a starting point. New calculations based on the output from an economic study could be done.

Other studies which might utilise the output from this study or which might be done interactively with this project include an investigation of the labour implications of CHP/dh use. However the major implications for labour are likely to arise from the capital formation process rather than current operation and this study would have to be preceeded by that discussed in section 9.3.1.3 above.

9.5 OPTIMISATION STUDIES

The problem as formulated in this project is that of determining the activity levels of a number of processes to meet a specified demand for a number of products when the number of available processes exceeds the number of products; the whole system being subject to a number of constraints arising both from technology and from the choice of a 'policy' option. The non-square matrix describing the production of the commodities may be treated by linear programming techniques to find an 'optimum' vector of activity levels where the optimum is measured by any of a number of possible objective functions. For example, it would be possible to pose questions of the type 'Which x vector will minimise the peak demand upon conventional electricity generation?' Although this might prove to be a major piece of work, it is likely that it would be extremely rewarding in giving indicators for possible policy design.

9.6 SUMMARY

A number of avenues for future research suggest themselves. Within the context of the present study alone, there is considerable scope for further investigation of the present topic by using alternative sets of assumptions about, for example, the variability of heat to power ratio and the capability for heat storage. Looking further afield, there is scope for using this physical model in tandem with an examination of the important economic aspects of the use of district heating.

10. POLICY IMPLICATIONS AND CONCLUSIONS

In this chapter the calculated and heuristic conclusions are briefly stated together with a number of conclusions for energy policy or for the policy of individual energy industries. Technological conclusions are also summarised and conclusions about the effectiveness of the modelling methodology used in the project are presented.

It should be noted that all of the conclusions presented here are features of the assumptions and the scenario specifications outlined in previous chapters. It would be inappropriate to regard them as specific features of CHP or district heating as such until appropriate sensitivity tests are completed. In particular, it should be noted that the conclusions refer specifically to CHP plant where the heat to power ratio is constant and operates at a constant level throughout each of four seasons. All the conclusions should be interpreted against the background of prevailing technology and merit order in 1977.

10.1 EFFECT OF CHP/DH USE UPON FUEL INDUSTRIES

10.1.1 System load factor for electricity generation

The general effect of CHP and HOB use is to reduce, quite substantially, the system load factor of the conventional power stations. This reduction is shown to be larger than might have been expected, given the highly seasonal nature of electricity demand due to heating. This means that electricity prices might rise by a considerable amount unless it proves possible to provide a general subsidy to conventional electricity production from heat sales. This conclusion highlights the necessity for ITOC-based systems and of not viewing the grid as a 'dump' for electricity generated by CHP plant.

(Section 8.2.3; Tables 8.7 to 8.10; Figures 8.4 to 8.11).

10.1.2 Power station merit order

The use of CHP plant, under the present sets of assumptions about heat to power ratio, will substantially reduce plant load factors of groups of power stations, including baseload plant. Particularly at high heat market penetrations and low heat to power ratios, there is a potential for whole groups of power stations to become redundant. It might be appropriate to phase CHP installation with the Electricity Supply Industry's developing plant closure programme and to use CHP plant (if that is what is desired) as replacement for conventional electricity generation plant.

(Section 8.2.3.5; Tables 8.11 and 8.12; Figures 8.13 to 8.16)

10.1.3 ITOC plant

It is a strong conclusion of this study that the use of CHP plant with fixed heat to power is very prejudicial to the system load factor of conventional generation plant and that the total installed capacity of back pressure plant should be very limited.

(Sections 8.2.2, 8.3.2 and 9.2.2; Table 9.2)

10.1.4 Coal requirements

Through the use of coal fired CHP plant, the coal industry could substantially increase its share of the low grade heat market. However, the use of district heating, especially from CHP plant will reduce direct sales of coal for low grade heating and more importantly, electricity. Direct use of coal for low grade heating in domestic circumstances is very inefficient. Even in baseload generating plant, utilisation is very inefficient. Thus district heating, although offering a larger market share to the coal industry, so reduces the size of the market by displacing less efficient processes, that the coal industry's output is likely to remain relatively unaffected by the use of coal fired CHP/dh or HOB/dh. This conclusion is in contradiction to the popular wisdom that district heating would be 'a good thing for the coal industry' and underestimates the indirect effect of displacing coal fired electricity generation.

(Section 8.2.1.3; Table 8.3; Figure 8.1)

10.1.5 Coal's market share

Athough for itself the Coal Industry might thus be fairly neutral towards CHP, the prevailing political climate favours diversity in energy supply in order that the country be not 'held to ransom' by sectional interests. The greatly increased dependency of the low grade heat market upon coal as a major (although indirect) fuel source might for this reason prove politically unpopular.

10.1.6 Gas requirements

Gas is a major supplier to the low grade heat market. The study confirms that if either CHP/dh or HOB/dh were introduced gas would suffer reductions in gas requirements and shows that these would lie between 9.3 and 12.5%. (30% market penetration by district heating) with negligible compensatory gains.

(Section 8.2.1.1; Table 8.2)

10.1.7 Gas-fired CHP

The use of gas fired CHP/dh increases total gas sales by 31% (30% penetration) showing that enhanced efficiency effects are outweighed by increased market share.

(Section 6.4.4; Tables 6.4 to 6.6, 6.8, 6.9 and 6.11; Figures 6.1 to 6.3)

10.1.8 Fuel oil requirements

The use of gas or coal fired CHP and HOBs of all types reduces the total requirements for liquid fuels by approximately 10%. Fuel oil has only a small share of the heating and electricity generation markets. However, oil fired CHP district heating systems increase oil requirements by 10% (based on 30% penetration of district heating).

(Section 8.2.1.4; Table 8.4)

10.1.9 Fuel oil imports

The use of oil as a fuel for CHP district heating plant, would increase the demand for light fuel imports by approximately 48%. Other CHP fuels reduce imports by between 47 and 57%. Heat only boilers reduce imported fuel demand by approximately 29% in the case of coal and gas-fired plant/ increase by 24% in the case of oil fired plant. (Based on 30% penetration by district heating.)

(Section 8.2.1.4; Table 8.5)

10.2 EFFECT OF DISTRICT HEATING TECHNOLOGY CHOICE

The conclusions drawn from a study such as this are much more heavily dependent upon the specification of the scenario than is usually assumed. The study has shown that many degrees of freedom are available for district heating scenarios. The conclusions outlined below are subject to the particular scenario specifications used in the thesis.

(Section 8.1)

10.2.1 Effect of fuel input type

Some of these conclusions have been itemised, in part, above.

(Sections 10.1.4 to 10.1.9)

10.2.1.1 Oil fired CHP/dh and HOB/dh

The net effect of oil fired district heating is to increase UK fuel oil requirements, imports being the marginal source.

(Section 8.2.1.4; Tables 8.5, 8.6)

10.2.1.2 Coal fired CHP/dh

The study has shown quite clearly that, except in the case of CHP plant with low heat to power ratios, the use of coal to supply CHP plant is more than offset by reductions in the coal burn in power stations, resulting in a small decrease in total coal burn.

(Section 8.2.1.3; Table 8.3; Figure 8.1)

10.2.1.3 Coal fired CHP plant with low heat to power ratio

Although the overall thermal efficiency of CHP plant of this type is still very much higher than even the best power station, a low heat to power ratio means that the CHP station is approaching the operation of a power station, with a lower electricity generating efficiency. However,

the heat output is insufficient to effect significant direct energy savings, resulting in a net increase in coal consumption.
(Section 8.2.1.3)

10.2.1.4 Gas fired CHP plant and HOB plant

The result of using gas fired district heating is to effect an overall reduction in fuel requirements (excepting gas itself in the case of CHP).
(Sections 6.4.4, 8.2.1.1; Tables 6.6, 8.2)

10.2.1.5 Nuclear CHP plant

The effect of nuclear powered CHP is to reduce conventional electricity production, through the production of electricity, and to reduce the requirements for other inputs to low grade heat production. Since the input of nuclear fuel is not recorded, the changes in the other fuel requirements may be seen as the baseline savings arising from CHP/dh use.
(Tables 8.2 to 8.5 and 8.7 to 8.15)

10.2.2 Effect of heat to power ratio

In scenarios specifying a particular district heating demand the effect of heat to power ratio is to vary the quantity of electricity produced by CHP plant and consequently displacing conventional electricity generation. The principal savings from district heating are found to occur through the displacement of inefficient heating plant. Part of these benefits occur by displacing electricity from the low grade heat market. Electricity generated by CHP plant displaces conventional electricity generation. However, the smaller the value of R, the greater the quantity of electricity displaced. Some of this will be baseload plant and consequently of a high efficiency, so that the actual saving will be smaller at low values of R. It should be remembered, however, that in the light of 10.1.1, conclusions about constant heat to power ratios are of limited applicability.
(Section 8.2.1.3)

10.2.2.1 Heat only boilers

Since the energy savings from the displacement of conventional electricity generation are not large, heat only boilers, with their greater effiency realise total energy savings comparable with those of CHP plant.
(Section 8.2.1.3, Table 8.14)

10.2.2.2 Power station activity levels

The activity level of the electricity supply industry is reduced overall by the use of district heating. This is manifest as a reduced system load factor, a substantial reduction in the output required of baseload and middle order plant and a greatly reduced minimum load. All these effects increase with reducing heat to power ratio and are likely to be very different where ITOC-based scenarios are investigated.
(Sections 8.2.3.2, 8.2.3.3, 8.2.3.4, 8.2.3.5, and Figures 8.2, 8.3 and 8.13 to 8.16)

10.2.2.3 Maximum heat market·penetration

There is a maximum penetration into the heat market by CHP derived heat. It has been shown that for a heat to power ratio this maximum penetration lies between 25 and 30% of the heat market. At this value, more electricity is produced by CHP plant than the total UK demand for electricity during certain periods.
(Sections 8.2.1.1 and 8.2.3.2)

10.2.3 Effect of plant efficiency

10.2.3.1 Maximum value of Z

No net energy saving occurs unless the ratios of the efficiencies of conventional power plant to conventional heating plant exceed the value of Z for the plant replacing it.
(Appendix 10)

10.2.3.2 Coal fired CHP plant

The efficiency of coal fired CHP plant has a negligible effect upon gas and oil requirements. There is a weak inverse relationship between CHP plant efficiency and total electricity requirements, due to the electricity input required to produce coal. Coal demand shows an inverse relationship with CHP plant efficiency.

(Tables 8.2 to 8.4 and 8.7)

10.2.4 Effects of market penetration

10.2.4.1 First order effects

The displacement of fuels and electricity from heat markets is linearly related to heat market penetration. The reduction in the overall activity of the electricity industry, attributable to direct displacement by CHP derived electricity is also linearly related to the penetration of the heat markets by district heating.

10.2.4.2 Second order effects

Second order effects arise through the fuel input requirements of electricity and are also strongly related to market penetration although not linearly due to the non-linear relationship between conventional electricity production and generation efficiency.

10.2.5 Heat only boilers

An examination of the total fossil fuel requirements of the scenarios examined yields the astonishing result that, with the exception of nuclear powered CHP, heat only boilers save more energy than does CHP. Although this is undoubtedly due to the high marginal efficiency of the electricity displaced by CHP plant, this counter-intuitive result requires further detailed examination.

(Table 8.14)

10.2.6 Synthetic natural gas

The effect of the use of SNG to replace North Sea gas is to raise the baseline coal requirement and the magnitude of the small electricity baseload used to produce that coal. The effects of district heating correspond fairly directly to those in the North Sea gas scenarios although with this enlarged coal baseline.
(Section 8.2.1.5, Table 8.17)

10.2.7 Total energy savings

Energy savings have been compared with those quoted elsewhere (eg Energy Paper 20) and have been found to be broadly comparable.
(Table 8.14)

10.3 FUTURE RESEARCH

Many possible areas of further research suggest themselves. The two highlighted here are seen as being the most immediate.

10.3.1 Heat only boilers

The reasons for the larger energy savings achieved by heat only boilers needs to be more fully explored.
(Section 10.2.2.1)

10.3.2 Heat to power ratio

Of all the lines of development suggested by the outcome of this research, its development to examine scenarios for CHP plant with variable heat to power ratio is the most immediate need.
(Section 9.2)

10.4 MODELLING CONCLUSIONS

Many of these conclusions have not been noted explicitly elsewhere and are therefore not section-referenced.

10.4.1 The 'minimalist' approach

The use of a minimalist, problem-orientated approach to modelling the UK energy system has yielded substantial dividents in terms of understanding the system although the temptation to include sectors for the sake of completeness is not always easy to resist. By building the model from the starting point of the problems posed in Chapter 2, it was easy to see what was necessary and what was not. As a direct consequence of this, all the data generated by the model was directly useful and relevant to the problem with no superfluity.

10.4.2 Processes and products

The distinction drawn between processes and products allows much greater clarity in thinking about technological change than could otherwise be achieved. It shows immediately, as the model is constructed, where technological options exist. As soon as the number of processes exceeds the number of products then an option exists for which the choice may be specified by an appropriate constraint form.

Models of the Sankey diagram type, do not have the advantage that this model has of presenting both information about product flows (the q vector) and about the contribution of each process (the x vector). Information about changes in relative levels of processes is essential for a clear understanding of technological change.

10.4.3 Structural simplicity

The linearity inherent in representing relationships through data has not proved to be a disadvantage, even though the modelling of non-linear processes has been central to the research. Indeed it has instead highlighted, in this case, the inability of electricity generated at one time to be used at another and enabled clear distinctions between groups of power stations to be made.

A disadvantage of this structural simplicity is the need for considerable quantities of data and the specification of a large number of processes and products. While this has not been a pressing disadvantage in this study, it is a potential problem for data management and computer CPU time in future studies of variable heat to power ratio.

Despite these reservations, the ease with which the sources of calculated effects can be tracked through the model gives the calculated results considerable credibility and has enabled the full realisation of the objective of enhanced understanding.

All the advantages of conventional input output modelling have been retained in the model described while most of the difficulties have been circumvented.

10.5 PERSONAL CONCLUSIONS

Although this project has spanned a considerable period of time, it has consistently been interesting, and frequently exciting, to pursue. Excitement comes from having one's ideas expanded or changed, in other words, from the learning process. It has been my intention that some of the excitement has been apparent in this thesis.

The project has brought me into contact with a wide range of intellectual disciplines with their differing perspectives. This too is exciting. On a wider scale, among all the things I have learned about research activity, I have been very impressed by the extent to which increasing the clarity with which one defines a problem, increases one's awareness of how to find its resolution, and of how many alternative ways there are of asking a seemingly simple question.

APPENDIX 1

Calculation of Z factor, heat to power ratio and efficiencies.

To consider the way in which the performance of CHP plant is measured, two CHP turbines will be compared with a conventional 200MW turbine. In this example calculation, the conventional turbine receives steam at 400°C and 30 bar. The turbine has an isentropic efficiency of 0.8 and exhausts at 0.04 bar (29°C). Under these conditions an output of 200 MW requires a steam flowrate of 218 kgs^{-1} (A.1.1). The cycle efficiency of such a turbine (if the steam cycle is a simple Rankine cycle with superheat) would be 29.5%, the heat supply rate being 678 MJs^{-1}.

This same turbine might be modified so tht all the steam is condensed at a pressure of 1.01 bar, at which pressure its temperature is 100°C. The entry conditions and steam flowrate would be the same. However, exhausting the steam into the condenser at this higher pressure would improve the isentropic efficiency since most of the irreversibilities occur at the low pressure end of the turbine which is no longer there (A.1.2). A typical value of isentropic efficiency for a steam turbine operating over this range might be 0.9. The steam turbine would, under these conditions, produce an output of 141 MW and the cycle efficiency would be 23.0%. Since the condensation temperature is higher, the heat input to the cycle is reduced (this can be seen by comparing figures A.1.1 and A.1.2) so that the heat supply rate is now 614 MJs^{-1}.

If it is further assumed that 70% of the heat transferred to the cooling water is usable, then the overall thermal efficiency, the Z factor and the heat to power ratio may be calculated. The available

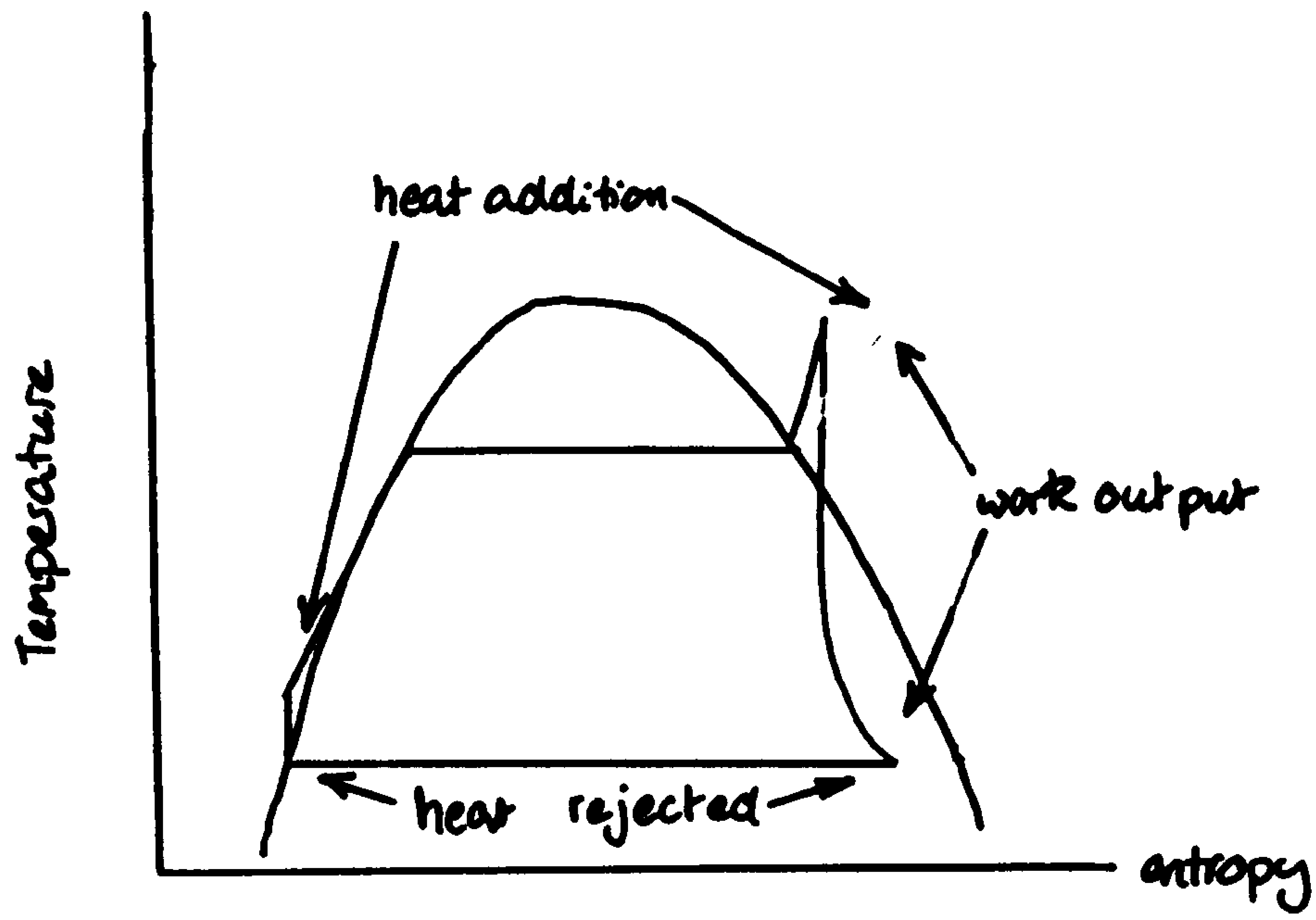


Figure A.1.1 Temperature-entropy diagram for conventional power plant

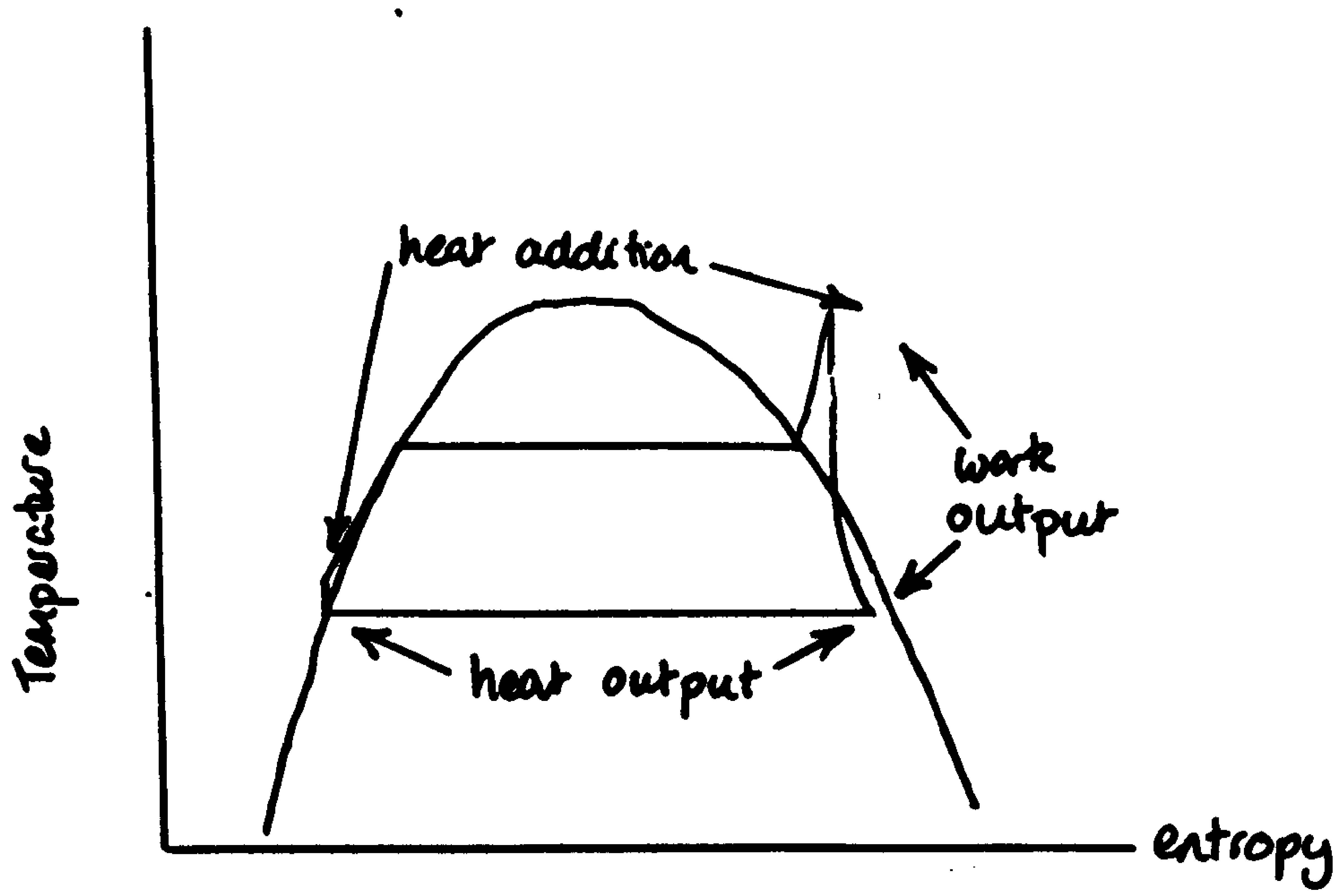


Figure A.1.2 Temperature-entropy diagram for CHP turbine quantity of heat is 331 MW

$$\text{overall efficiency} = \frac{\text{useful heat o/p + electrical}}{\text{heat input rate}}$$

$$= \frac{331 + 141}{614} \times 100\%$$

$$= 77\%$$

Z factor is calculated on the basis of the same steam conditions and flowrate at the turbine entry nozzle.

$$Z = \frac{\text{electrical o/p lost}}{\text{useful heat o/p gained}}$$

$$= \frac{200 - 141}{331}$$

$$= 0.18$$

$$\text{Heat to power ratio, } R = \frac{\text{heat o/p}}{\text{electrical o/p}}$$

$$= \frac{331}{141}$$

$$= 2.35$$

The above comparison deals with what is essentially a conversion. This is equivalent to comparing the performance of a conventional turbine with its performance as a back pressure turbine. An alternative approach is to examine what would happen if the 678 MJs^{-1} of heat previously supplied to the conventional turbine were instead supplied to comparable turbines operating as CHP plant. Comparability implies the same turbine entry conditions but steam flowrate is greater than in the last example to account for the increased heat flowrate. The distinction is illustrated in figure A.1.3. Case 3 is essentially a scaled up version of case 2 but the Z-factor, because it is a comparative figure is reduced.

In practice, CHP plant may be somewhat less straightforward than that illustrated in figure A.1.1 and A.1.2 but if the heat supply rate, heat delivery rate and electrical output are known then the electrical efficiency, overall efficiency, and heat to power ratio may be calculated. Comparison with equivalent conventional plant may be made either on the basis of steam flowrate or on the basis of heat supply rate by use of Z-factor.

A common form of CHP turbine is the intermediate take-off condensing turbine. This is best described as a development of a conventional electricity-only turbine in which a proportion y of the steam is extracted at an intermediate take off point and passed to a separate condenser where the latent heat is made available as useful heat. The remaining steam is expanded further and condensed in the normal way. The temperature entropy diagram for the simplest form of this plant is shown in figure A.1.4. Using the steam conditions used in the example above the inputs and outputs required with steam flowrate of 218 kgs^{-1} may be calculated by treating the cycle as the sum of (1-y) times the inputs and outputs of the conventional generating turbine and y times the outputs and inputs of the back pressure turbine.

$$\begin{aligned}
\text{heat input rate} &= 678\ (1-y) + 614y\ MJs^{-1} \\
&= 678 - 64y\ MJs^{-1} \\
\text{electrical output} &= 200\ (1-y) + 141y\ MW \\
&= 200 - 59y\ MW \\
\text{heat output} &= 331y\ MJs^{-1}
\end{aligned}$$

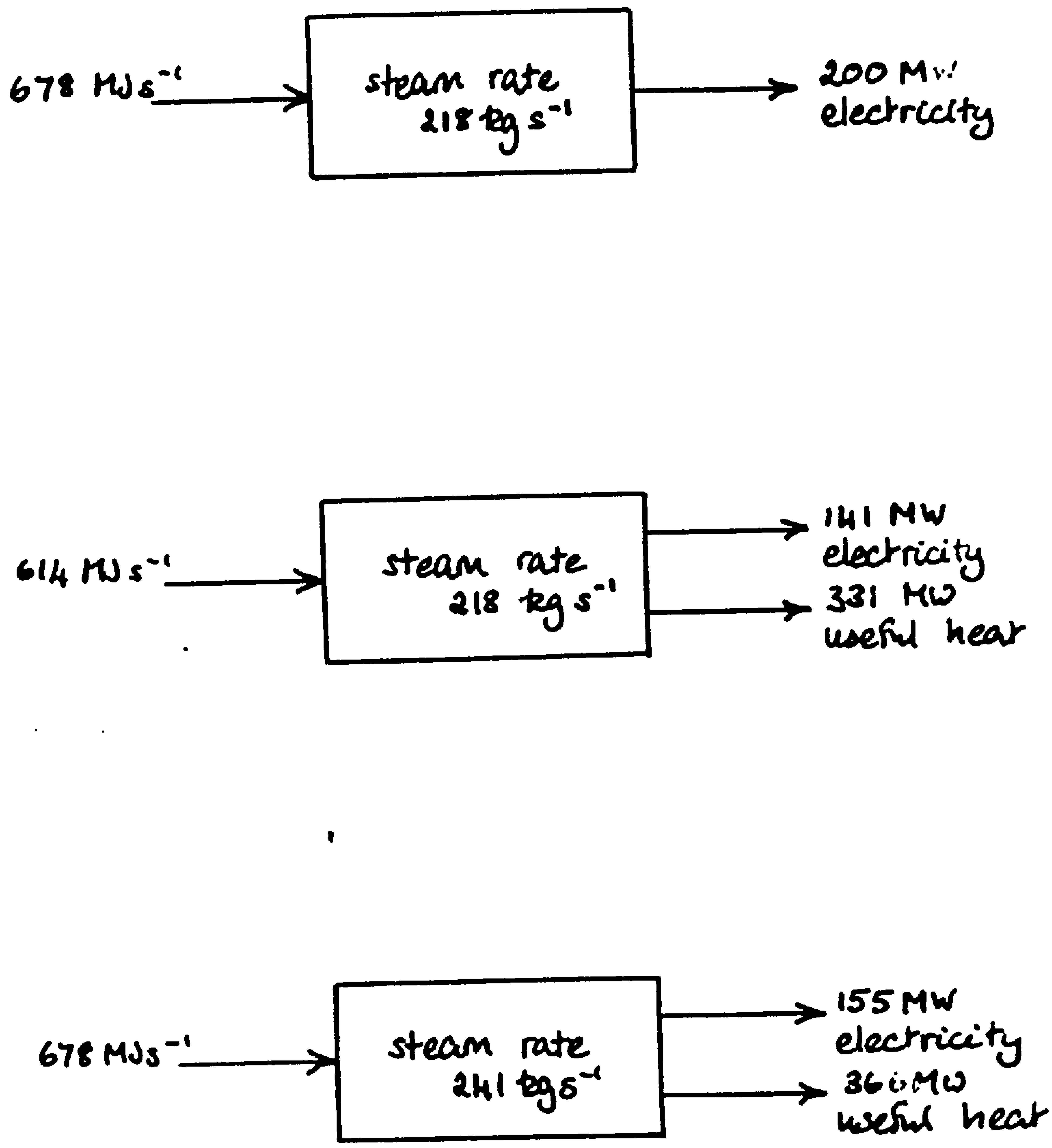


Figure A.1.3 Comparison of CHP plant with equivalent conventional plant

1) conventional power plant

2) CHP plant with same stream flowrate

electrical efficiency = 23%
overall efficiency = 77%
Z = 0.18
R = 2.35

3) CHP plant with same heat supply addition rate

electrical efficiency = 23%
overall efficiency = 77%
Z = 0.12
R = 2.35

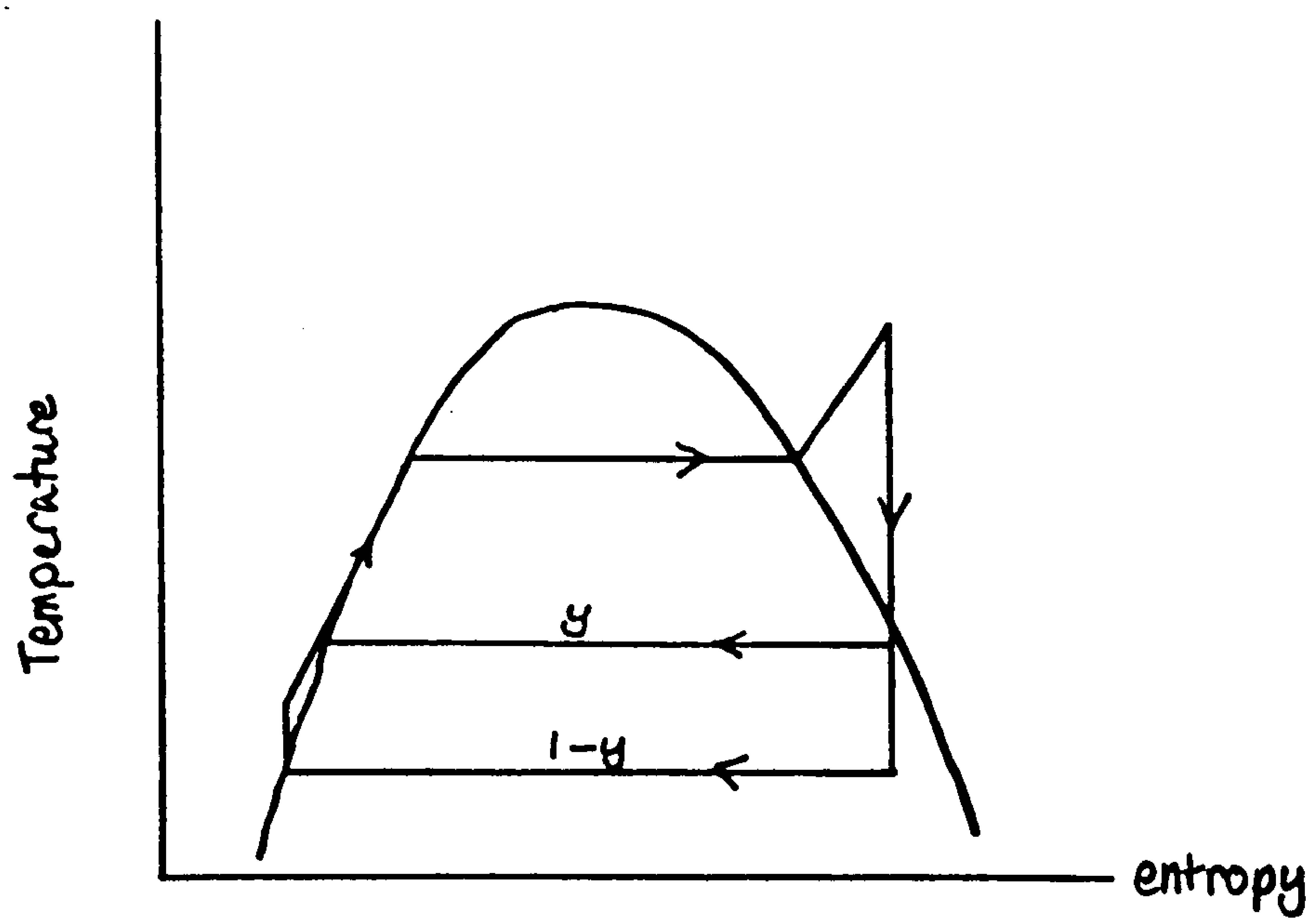


Figure A.1.4 Temperature-entropy diagram for ITOC turbine

The performance indeces are calculated in exactly the same way as before.

$$\text{electrical efficiency} = \frac{200 - 59y}{678 - 64y} \times 100\%$$

$$\text{overall thermal efficiency} = \frac{200 + 272y}{678 - 64y} \times 100\%$$

$$\text{heat to power ratio, } R = \frac{331y}{678 - 64y}$$

$$Z = \frac{59y}{678 - 64y}$$

APPENDIX 2

Comparison of CHP stations and electricity power stations.

(The Appendix is based upon an article written by the author and David Crabbe and published in Electrical Review 210 26th February 1983)

It is generally presumed that because a combined heat and power station based upon steam turbines produces less actual electricity than a conventional power station using the same quantity of fuel, this deficit in electricity generating capacity must be made up by the installation of additional electricity generating capacity elsewhere in the system (for example see Energy Paper 20 (A.2.1) and Wright (A.2.2). Much of the discussion focusses around the way in which this additional capacity should be charged to the CHP plant.

The idea that CHP stations necessarily reduce the useful electricity supply capability of the electricity system is based on a false premise. If the purpose for which electricity is used by consumers is examined, then the conclusion must be drawn that CHP stations may yield a net increase in the useful quantity of electricity available to consumers.

This conclusion arises from the observation that 25% of electricity now generated is used to produce low grade heat (at less than 100°C); a market which could be supplied by the heat output from a CHP station.

In the electricity-only power station illustrated in Figure A.2.1, 100 units of fuel are burned to produce η units of electricity where η is the percentage efficiency of the power station. Of these η units of electricity $p\eta$ will be used to produce low grade heat and the remaining $(1 - p)\eta$ units will be used for 'other purposes'.

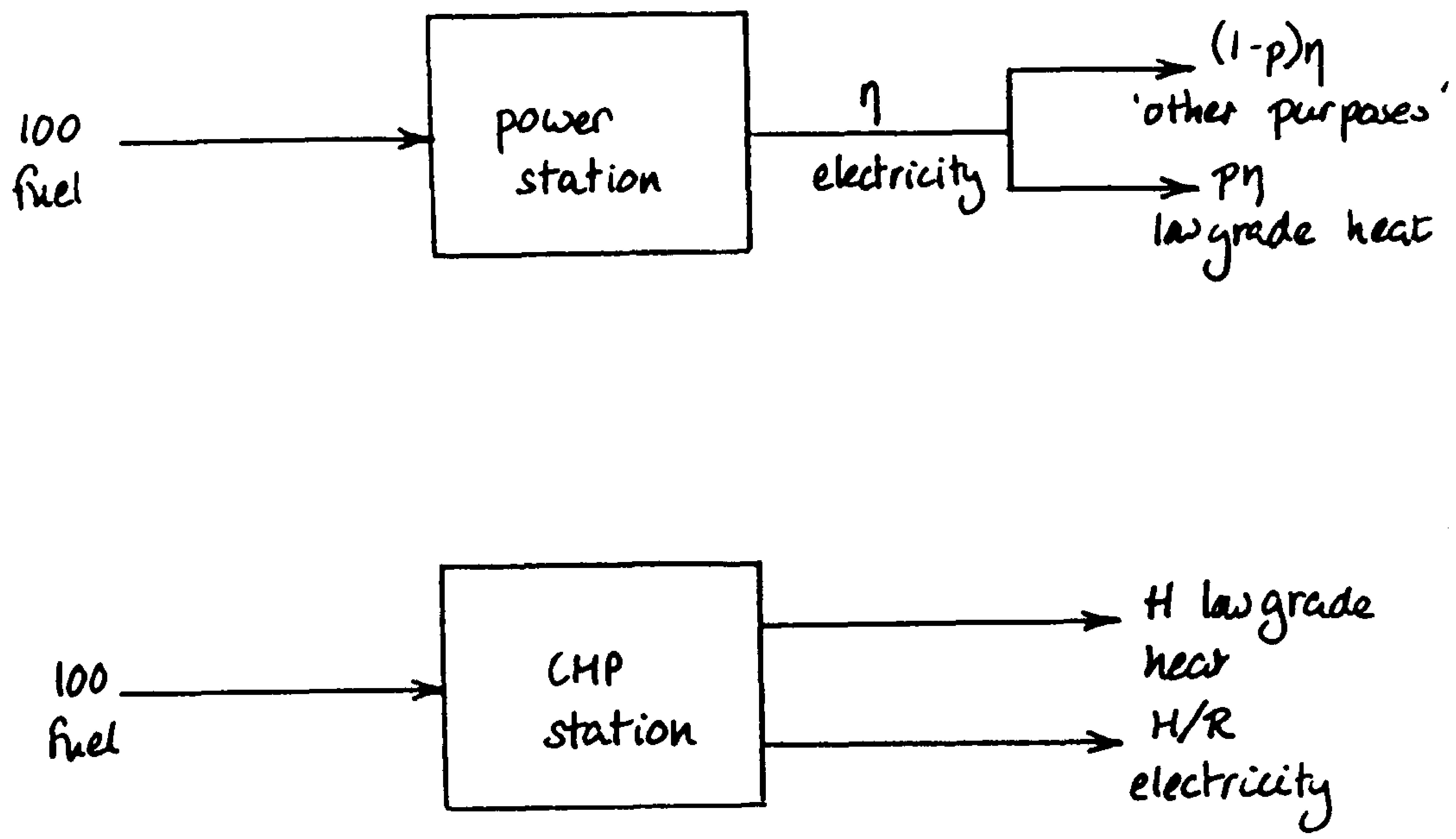


Figure A.2.1 Comparison of conventional power plant and CHP plant

A comparable CHP station with the same fuel input produces heat and power in the ratio R. If the heat output from the power station is H units then we can use the definition of Z to express the heat and electricity outputs of the CHP power station in terms of Z and R.
By definiton

$$Z = \frac{\text{electricity output lost}}{\text{heat output gained}} \qquad \text{A2.1}$$

$$= \frac{\eta - H/R}{H}$$

rearranging

$$H = \frac{\eta R}{ZR + 1}$$

and so, heat output from CHP station $= \dfrac{\eta R}{ZR + 1}$ A2.2

and electricity output from CHP station $= \dfrac{\eta}{ZR + 1}$ A2.3

The heat generated by the power station will be able to meet the market formerly met by electricity from the power station if

$$\frac{R\eta}{1 + RZ} \geqslant p\eta \qquad \text{A2.4}$$

This condition may be simplified to

$$R \geqslant \frac{p}{1 - pZ} \qquad \text{A2.5}$$

If it is assumed that this condition is met, then all the electricity from the CHP station will be available to meet the 'other purposes' electricity demand. This demand too will be fully met if

$$\frac{\eta}{1 + RZ} \geqslant (1 - p)\eta \qquad \text{A2.6}$$

which, if rearranged simplifies to

$$\frac{p}{(1-p)Z} \geqslant R \qquad \text{A2.7}$$

Combining these conditions A2.5 and A2.7 gives

$$\frac{p}{(1-p)Z} \geqslant R \geqslant \frac{p}{1-pZ} \qquad \text{A2.8}$$

which simplifies to

$$1 \geqslant Z \qquad \text{A2.9}$$

This condition is easily met, since as a consequence of the second law of thermodynamics, Z is always less than one. It can be seen that the crucial condition is then that expressed by equation A2.5. This is perhaps more usefully expressed in terms of

$$\frac{R}{1+RZ} \geqslant p \qquad \text{A2.10}$$

Although this condition is not easy to analyse, it is nonetheless easy to meet. For heat delivered at or below 110°C, and allowing a substantial margin for losses, Z can be identified as lying between 0.145 and 0.170 and if as in recent years $p \simeq 0.25$, then the minimum value of R would be 0.26 in order that both heat and electricity markets are fully met by the CHP plant.

Since R is almost always greater than 0.25, in order to justify the additional expense and complexity of the plant, it is an important conclusion that almost any CHP station will be able to serve larger heat <u>and</u> electricity markets than a power station with the same fuel input. The introduction of CHP technology thus leads to a surplus electricity capacity rather than a shortfall as commonly supposed. This is illustrated in figure A2.2.

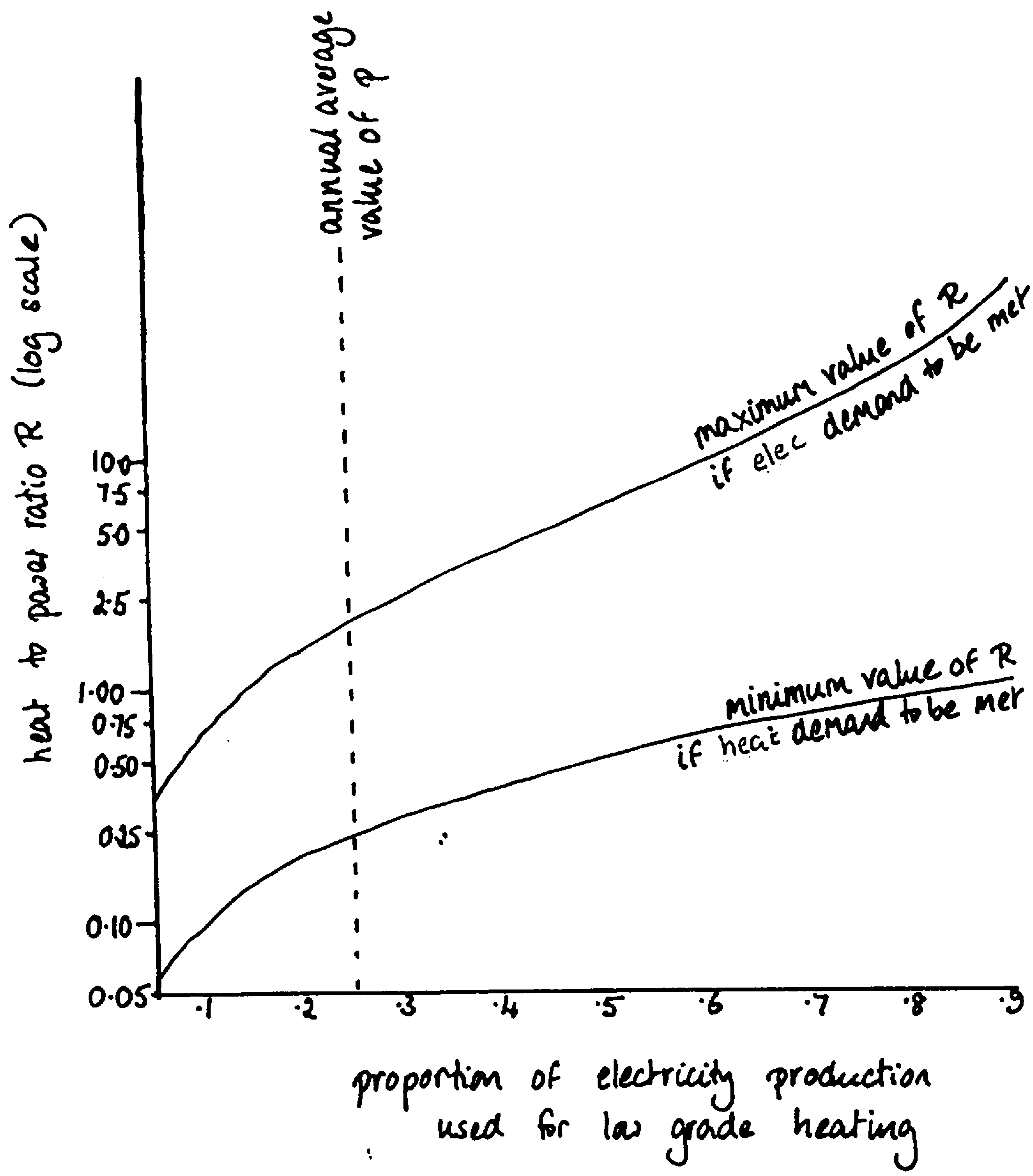


Figure A.2.2 Maximum and minimum values of R, the heat to power ratio, to replace conventional power stations

APPENDIX 3

Calculation of example coefficient matrices and associated Leontief inverses.

A two sector economy is described in which, during the data year, industry one produces 10 units of commodity one using an input of 4 units of commodity two. Industry two produces 8 units of commodity two, its principal product in conjunction with 3 units of commodity one, which is the non-principal product of the industry. Industry two requires 5 units of commodity one as an input to its production.

Thus $$A = \begin{pmatrix} 10 & 3 \\ 0 & 8 \end{pmatrix}$$

and $$B = \begin{pmatrix} 0 & 5 \\ 4 & 0 \end{pmatrix}$$

The total production vector for the base year q_0, is obtained by summing the rows of A

$$q_0 = \begin{pmatrix} 13 \\ 8 \end{pmatrix}$$

The final demand vector for that year f_0 is the row sums of the vector A-B

$$f_0 = \begin{pmatrix} 8 \\ 4 \end{pmatrix}$$

The vector of industry outputs g_0 is obtained by summing the column totals of A

$$g_0 = \begin{pmatrix} 10 \\ 11 \end{pmatrix}$$

Hence the product mix matrix for which

$$p_{ij} = a_{ij}/g_j$$

$$P = \begin{pmatrix} 10/10\ (1.000) & 3/11\ (0.273) \\ 0 & 8/11\ (0.727) \end{pmatrix}$$

and the input mix matrix

$$r_{ij} = b_{ij}/g_j$$

$$R = \begin{pmatrix} 0 & 5/11\ (0.455) \\ 4/10\ (0.400) & 0 \end{pmatrix}$$

The market share matrix has rows representing the market shares of industries and columns representing commodities

$$d_{ij} = a_{ji}/q_i$$

$$D = \begin{pmatrix} 10/13\ (0.769) & 0 \\ 3/13\ (0.231) & 1 \end{pmatrix}$$

Hence, using the commodity technology assumption for both industries

$$X = RP^{-1}$$

$$X = \begin{pmatrix} 0 & 5/8\ \ (0.625) \\ 4/10\ (0.400) & -3/20\ (-0.150) \end{pmatrix}$$

And the associated Leontief inverse for the commodity technology assumption

$$(I - X)^{-1} = \begin{pmatrix} 17/12\ (1.417) & 25/24\ (1.042 \\ 2/3\ \ (0.667) & 5/3\ (1.667) \end{pmatrix}$$

If alternatively the industry technology assumption is applied to the whole economy

$$X = RD$$

$$X = \begin{pmatrix} 15/143\ (0.105) & 5/11\ (0.455) \\ 40/130\ (0.308) & 0 \end{pmatrix}$$

And the associated Leontief inverse,

$$(I - X)^{-1} = \begin{pmatrix} 143/108\ (1.324) & 65/108\ (0.602) \\ 44/108\ (0.407) & 128/108\ (1.185) \end{pmatrix}$$

We might speculate that in some year other than the base year the final demand vector becomes

$$f = \begin{pmatrix} 7 \\ 5 \end{pmatrix}$$

The vector of total commodity requirements can be calculated for either technology.

For commodity technology

$$q = (I - X)^{-1} f$$

$$= \begin{pmatrix} 17/12 & 25/24 \\ 2/3 & 5/3 \end{pmatrix} \begin{pmatrix} 7 \\ 5 \end{pmatrix}$$

$$= \begin{pmatrix} 12.417 \\ 8.667 \end{pmatrix}$$

For industry technology

$$q = (I - X)^{-1} f$$

$$= \begin{pmatrix} 143/108 & 65/108 \\ 44/108 & 128/108 \end{pmatrix} \begin{pmatrix} 7 \\ 5 \end{pmatrix}$$

$$= \begin{pmatrix} 12.278 \\ 8.778 \end{pmatrix}$$

APPENDIX 4

Example of constraint use to investigate technological change.

The use of the 'empty' rows in the make and absorption matrices to investigate substitution between processes, is best demonstrated by the use of a small matrix, describing a very simple economy. The demonstration industrial system is described in table A4.1.

A wide range of scenarios can be investigated but two scenarios will be demonstrated here, in each case in conjunction with a change in final demand for one of the commodities.

Scenario 1 investigates the consequence of increasing the electricity output from nuclear power stations to 10 kWh x 10^{15}/year (a technological change) together with the constraint that coal imports should be reduced to zero (a policy constraint). All other conditions remain the same.

This is in many ways a typical scenario demonstrating the interaction of constraints. The change in electricity generation technology may well take place in response to a general policy requirement to reduce imports. That a constraint upon one of the sources of coal is required can be deducted intuitively by observing that some coal powered generation will be displaced and that a reduction in coal production by one of its sources will be required. A constraint is needed to specify how or which one.

The specified scenario can be written in matrix form:

A-B	coal mines	coal imports	coal fired power stations	nuclear power stations	manufacturing ind. & services	final demand	total production
coal	100	20	-80	-	-10	30	120
electricity	-5	-	25	5	-10	15	30
goods and services	-	-	-	-	1	1	1
year zero activity levels	1	1	1	1	1		
imports flag vector	0	1	0	0	0		

Table A4.1 Year zero description of demonstration industrial system

$$A - B = \left(\begin{array}{ccccc} 100 & 20 & -80 & 0 & -10 \\ -5 & 0 & 25 & 5 & -10 \\ 0 & 0 & 0 & 0 & 1 \\ \hdashline 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{array}\right) \qquad \text{A4.1}$$

where the columns correspond to the processes (in order) of Table A4.1 and the rows represent coal, electricity, and goods and services together with the two constraint rows. In this industrial system, coal is measured in Mtonnes, electricity in kWh x 10^{15} and goods and services in multiples of 'year zero production'. Ones are entered in the constraint rows in the columns representing the processes whose production level is to be specified. Trial demand elements corresponding to the constraints are determined in this case by the following specification

$$f_j = \frac{\text{required i output of process j}}{a_{ij}}$$

hence, for coal imports

$$f_4 = 0/20 = 0$$

for the nuclear power stations

$$f_5 = 10/5 = 2$$

Other final demand elements remain the same.

Thus

$$f = \left(\begin{array}{c} 30 \\ 15 \\ 1 \\ \hdashline 0 \\ 2 \end{array}\right)$$

The inverse, $(A - B)^{-1}$. and the intensities matrix $A(A - B)^{-1}$ are independent of specified final demand and of the value of the constraint which is entered in f. The intensities matrix corresponding to the specification of A - B in equation A4.1 is thus

$$A(A - B)^{-1} = \begin{pmatrix} 1.190 & 3.810 & 50 & -3.810 & -19.048 \\ 0.060 & 1.190 & 12.5 & -1.190 & -0.952 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

It is useful to explore the meaning of the elements in this matrix. Those in column one describe the total requirements for the production of one unit of coal. Note that these are the <u>marginal</u> requirements of coal production which, because the importing process is constrained, will come from mines. Similarly element m_{12}, the coal intensity of electricity production describes the coal requirement for the marginal electricity production process, which in this case is specified as being the coal fired process since output from the alternative, nuclear, process is fixed. The elements in columns four and five (rows four and five are the constraint rows in A - B), describe the shadow cost of fixing the constraints element in f at one. In other words fixing the value of f_4 at one (as opposed to zero), <u>reduces</u> the total requirement for coal by 3.810 Mtonnes and reduces the total electricity requirement by 1.190 kWh x 10^{15}.

Vectors x and q are dependent upon f so that

$$x = (A - B)^{-1} f$$

$$= (A - B)^{-1} \begin{pmatrix} 30 \\ 15 \\ 1 \\ 0 \\ 2 \end{pmatrix}$$

$$= \begin{pmatrix} 1.048 \\ 0 \\ 0.81 \\ 2 \\ 1 \end{pmatrix}$$

and

$$q = A(A - B)^{-1} \begin{pmatrix} 30 \\ 15 \\ 1 \\ 0 \\ 2 \end{pmatrix}$$

$$= \begin{pmatrix} 104.75 \\ 30.23 \\ 1 \\ 0 \\ 1 \end{pmatrix}$$

Thus the scenario specification that nuclear power station output be doubled while coal imports are reduced to zero requires that a 4.8% increase in activity take place in the coal mines (ie a 4.8% increase in mine output) together with a 19% reduction in activity of the coal fired power stations.

A scenario may be specified in which there are changes not only in technology and policy but in final demand as well. For example, a 10% increase in demand for non-energy goods and services may occur so that, for scenario 1

$$f = \begin{pmatrix} 30 \\ 15 \\ 1.1 \\ 0 \\ 2 \end{pmatrix}$$

in this case

$$x = \begin{pmatrix} 1.098 \\ 0 \\ 0.860 \\ 2 \\ 1.1 \end{pmatrix} \qquad q = \begin{pmatrix} 109.762 \\ 31.488 \\ 1.1 \\ 0 \\ 2 \end{pmatrix}$$

Scenario 2. In this scenario it is required that the output of the coal fired power stations be reduced by 25% while coal imports and coal mined retain their present proportions. Thus

$$A - B = \begin{bmatrix} 100 & 20 & -80 & 0 & -10 \\ -5 & 0 & 25 & 5 & -10 \\ 0 & 0 & 0 & 0 & 1 \\ 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

and

$$f_5 = (1 - .25)\frac{(20)}{20}$$

$$= 0.75 \text{ (from equation 4.15)}$$

The final demand vector for this scenario is thus

$$f = \begin{pmatrix} 30 \\ 15 \\ 1 \\ 0 \\ .75 \end{pmatrix}$$

This yields

$$x = \begin{pmatrix} 0.833 \\ 0.833 \\ 0.750 \\ 2.083 \\ 1 \end{pmatrix} \qquad q = \begin{pmatrix} 100 \\ 29.167 \\ 1 \\ 0.833 \\ 0.75 \end{pmatrix}$$

As expected the activities of coal production are decreased since the coal requirements for electricity production is decreased.

The matrix of intensities can usefully be compared with that of the previous example.

$$A(A - B)^{-1} = \begin{pmatrix} 1 & 0 & 10 & 0 & 80 \\ 0.0417 & 1 & 0 & 10.417 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0.0083 & 0 & 0.0833 & 0.0167 & .6667 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

The self intensity of coal is here one since the marginal source of electricity is nuclear power stations which do not themselves require coal as an input. The reduced electricity intensity of coal is seen in the second element of the first column. Element m_{14} is the input of coal required to produce unit activity of coal imports. At first sight this seems strange since coal importing, as a process has no direct input. However, the reason for this apparent anomoly becomes clear when it is realised that in this scenario, coal importing is tied to coal mining. Other substantial changes between this and the previous scenario is the sensitivity of production requirements to the final demand for goods and services. Since the marginal source of electricity is now nuclear plant, the requirements for coal and electricity relates only to direct inputs.

This simple example clearly demonstrates the substantial effects that differing scenario specifications have upon activity levels, total requirements and intensities. It also shows clearly the extent to which assumptions, unless clearly specified make the results of energy analysis-type activity meaningless.

APPENDIX 5

Data entries for make and absorption matrices (Element numbers refer to the 40 x 40 matrices of the pilot study: Energy Production and Use, see Table 5.1).

1. Gas

Data describing the production and absorption of gas is taken from Dig. of Energy Stats. 1979, tables 55 and 56. Only net productions or absorptions are recorded for each process.

Statistical differences (less than 6% of total inland consumption) are distributed proportionally among the row entries.

$a_{1,1}$ = 15449 Mtherms

$a_{1,2}$ = 162 Mtherms

$a_{1,4}$ = 406 Mtherms

$a_{1,7}$ = 998 Mtherms

$b_{1,9}$ = 519 Mtherms

$b_{1,14}$ = 153 Mtherms

$b_{1,15}$ = 688 Mtherms

This gives a total availability figure of 17016 Mtherms of which a total of 1360 Mtherms are accounted for. Of the remaining 15656 Mtherms for final demand and 'other manufacturing and services', some will be for heating purposes. The appropriate split is described in section 9 of this Appendix.

2. Coal

From the Dig. of En. Stats 1979, table 17. Stock changes, imports (2% of domestic production), overseas shipments are all very small and are aggregated with total production

$a_{2,3}$ = 124.5 million tonnes

$b_{2,4}$ = 20.6 million tonnes

$b_{2,10}$ = 80 million tonnes

$b_{2,15}$ = 0.2 million tonnes

all of the coal delivered to domestic premises is assumed to be for low grade heat production so that

$b_{1,24}$ = 11.2 million tonnes

Of the remaining 12.5 million tonnes, 2.9 million tonnes are exported and the remaining delivered to 'other manufacturing and services' for heating and other purposes (such as raising high temperature heat) (see section 9 of this Appendix).

3. Coke

Data taken from Dig. En. Stats 1970 Tables 30 and 31 'Other Manufactured solid fuels' are added to coke.

Thus:

$a_{3,4}$ = 13.6 million tonnes

$b_{3,15}$ = 8 million tonnes

$b_{3,25}$ = 3.7 million tonnes

f_3 = 1.2 million tonnes (known stock changes and exports)

Other coke is sold to 'other manufacturing and services' either for low grade heating (entry $b_{3,20}$) or for high grade heating (entry $b_{3,16}$) (see section 9 below).

4. Crude oil

Digest of En. Stats 1979 tables 44 to 47. On-shore production, and condensate production (together less than 1% of total domestic production) are added to North Sea production. Thus

$a_{4,5}$ = 37540 thousand tonnes

$a_{4,6}$ = 70697 thousand tonnes

$b_{4,7}$ = 93614 thousand tonnes

f_4 = 14623 thousand tonnes (exports)

5. Refinery products

Dig. of Energy Stats, tables 44, 52 and 54.

Refinery products are disaggregated as fuel oil (for both high grade heat production and low grade heat production) and other oils (including motor spirit). Since this is a somewhat unusual basis for disaggregation, being functionally based rather than by boiling point, it is necessary to determine the destination of refinery products before determining the way in which total refinery production is split between its two products. Thus

$b_{5,11}$ = 10600 thousand tonnes

$b_{5,14}$ = 5747 thousand tonnes

$b_{5,15}$ = 2940 thousand tonnes

$b_{6\ 16}$ = 3491 thousand tonnes

$b_{5,21} + b_{5,16}$ = 6081 thousand tonnes

$b_{5,26}$ = 3310 thousand tonnes

$b_{6,17}$ = 1342 thousand tonnes

$a_{5,1}$ = 704 thousand tonnes (naptha)

f_5 = 16292 thousand tonnes

f_6 = 16419 thousand tonnes

Thus; $a_{5,7}$ = 50563 thousand tonnes

$a_{6,7}$ = 33338 thousand tonnes

6. Electricity produced

Dig. of Energy Stats 1979 tables 68 and 69.

Mixed firing is allocated proportionately between coal and oil. Net output from pumped storage facilities and from hydroelectric installations are aggregated with nuclear plant. Exports are subtracted from net production by gas fired plant (ie peaking plant). Thus

$$a_{7,9} = 515 \text{ GWh}$$
$$a_{7,10} = 175016 \text{ GWh}$$
$$a_{7,11} = 32889 \text{ GWh}$$
$$a_{7,12} = 34573 \text{ GWh}$$

All non-public sector electricity generation is allocated to industry and does not appear as an entry since all electricity is self consumed.

7. Electricity sold

Dig. of Energy Stats. table 66.

$$b_{8,3} = 5090 \text{ GWh}$$
$$b_{8,4} = 210 \text{ GWh}$$
$$b_{8,7} = 920 \text{ GWh}$$
$$b_{8,15} = 11390 \text{ GWh}$$
$$b_{8,16} + b_{8,22} = 115830 \text{ GWh}$$
$$b_{8,17} = 2930 \text{ GWh}$$
$$b_{8,27} + f_8 = 41108 \text{ GWh}$$

8. Petrochemicals, iron and steel, other goods and services and transport: all are expressed in terms of '1977 net output'. Imports are aggregated in each sector (in the case of iron and steel and other goods and services see Chapter 6 section 6.4.2). Thus:

$a_{9,14} = 1$

$a_{10,15} = 1$

$b_{9,16} = 1$

$b_{10,16} = 1$

$a_{11,16} = 1$

$a_{12,17} = 1$

$a_{11,17} = -1$

Note the coefficients in each case represent the net production of the sector; internal circulation is disguised by the level of aggregation.

9. Low grade heat

The introduction of CHP technology would make available a new source of low grade heat, marketed and distributed as such. A way of representing the low grade heat which it will displace is therefore required. This is done by postulating 'processes' by which fuels may be converted into low grade heat.

9.1 Domestic sector

Figures for fuel deliveries to the domestic sector have already been derived (see above) and are confirmed by Bush and Matthews, who give separate figures for quantities used for low grade heating purposes. There is considerable doubt about the efficiency with which each of the fuels is converted to low grade heat in the domestic situation, especially given the diverse nature of the technologies employed. Leech gives data for efficiencies which can be used for on and off season heating. An average efficiency for domestic hot water can be derived if it is assumed that the two seasons are of equal length. Bush and Matthews give further data to show the split between domestic hot water and space heating. Thus:

$a_{14,23}$ = 3193 Mtherms

$b_{1,23}$ = 5304 Mtherms

$a_{14,24}$ = 1032 Mtherms

$b_{2,24}$ = 11.2 million tonnes

$a_{14,25}$ = 341 Mtherms

$b_{3,25}$ = 3.7 million tonnes

$a_{14,26}$ = 968 Mtherms

$b_{5,26}$ = 3310 thousand tonnes

$a_{14,27}$ = 1103 Mtherms

$b_{8,27}$ = 41108 GWh

9.2 Institutional and commercial premises

Data for these sectors is not fully broken down by Bush and Matthews, and hence the data do not map directly to the input-output format. However, the delivered energy inputs to these sectors has already been determined and it is assumed that market shares are the same for each sector (the implication of this assumption is that the differing distribution of shops, offices, hospitals etc. between the public administration and industrial/commercial sectors can be ignored or that their energy consumptions do not differ significantly either in type or conversion efficiency.

Energy sold for space heating and domestic hot water is given by Bush and Matthews and the sales to each sector, inferred from both Bush and Matthews and previously derived values are as follows:

$b_{1,18}$ = 1151 Mtherms

$b_{2,19}$ = 2 million tonnes

$b_{3,20}$ = 0.7 million tonnes

$b_{5,21}$ = 6081 thousand tonnes

$b_{8,22}$ = 13820 GWh

It has not proved possible to discover any data about the efficiency of commercial/administration heating systems. It has therefore been assumed that for each unit of fuel burned in the domestic sector, 10% of the energy wasted would be saved if that unit of energy were used in the commercial sector ie

$$\eta_{comm} = 0.1 + 0.9\eta_{dom}$$

Thus

$a_{13,18}$ = 739 Mtherms

$a_{13,19}$ = 218 Mtherms

$a_{13,20}$ = 76 Mtherms

$a_{13,21}$ = 1857 Mtherms

$a_{13,22}$ = 377 Mtherms

Data for CHP/dh technologies is loosely based upon those discussed in Energy Paper 20, appendix 2, normalised to 1 GWh installed electrical capacity.

CHP/dh technology 1	$a_{7,28}$	= 8760 GWh
	$a_{15,28}$	= 1187 Mtherms
	$b_{5,28}$	= 4112 thousand tonnes (diesel)
CHP/dh technology 2	$a_{7,29}$	= 8760 GWh
(heat:power ratio = 2.4)	$a_{15,29}$	= 717 Mtherms
	$b_{2,29}$	= 4.8 million tonnes
CHP/dh technology 3	$a_{7,30}$	= 8760 GWh
(heat:power ratio = 2.4)	$a_{15,30}$	= 717 Mtherms
	$b_{2,30}$	= 5.1 million tonnes
CHP/dh technology 4	$a_{7,31}$	= 8760 GWh
(heat:power ratio = 2.1)	$a_{15,31}$	= 300 Mtherms
	$b_{2,31}$	= 4.24 million tonnes

CHP/dh technology 5	$a_{7,32}$	=	8760 GWh
(nuclear powered:R = 2.4)	$a_{15,32}$	=	717 Mtherms
CHP/dh technology 6	$a_{7,33}$	=	8760 GWh
(nuclear powered:R = 2.2)	$a_{15,33}$	=	657 GWh
CHP/dh technology 7	$a_{8,34}$	=	8760 GWh (electricity sold)
	$a_{13,34}$	=	598 Mtherms (commercial heat delivered)
	$b_{1,34}$	=	1196 Mtherms
CHP/dh technology 8	$a_{8,34}$	=	8760 GWh (electricity sold)
	$a_{13,34}$	=	534 Mtherms (domestic heat delivered)
	$b_{1,34}$	=	1196 Mtherms (domestic heat delivered)
HOB/dh technology 9	$a_{15,36}$	=	2988 Mtherms
	$b_{2,36}$	=	1.5 million tonnes
HOB/dh technology 10	$a_{15,37}$	=	2988 Mtherms
	$b_{5,37}$	=	577 thousand tonnes
HOB/dh technology 11	$a_{15,38}$	=	2988 Mtherms
	$b_{1,38}$	=	365 Mtherms

The processes of transmission convert heat produced by CHP and HOB plant into heat delivered. The presence of these two processes allows the total penetration of piped heat into the market to be specified by constraint entries. The value of the entries is total annual demand for heat in the domestic and non-domestic sectors.

Thus:

$$a_{13,39} = 3267 \text{ Mtherms}$$

$$b_{15,39} = 3267 \text{ Mtherms}$$

and $$a_{14,40} = 6637 \text{ Mtherms}$$

$$b_{15,40} = 6637 \text{ Mtherms}$$

Synthetic natural gas production: coal is converted to fuel gas with a thermal efficiency of 65%.

$$a_{1,2} = 162.5 \text{ Mtherms}$$

$$b_{2,2} = 1 \text{ million tonnes}$$

A speculative CHP programme was specified in which a number of CHP/dh technologies act together. This was specified as follows:

100 Mtherms of coal-fired heat only boilers

.5 GW electrical capacity of technology 3 (coal)

.5 GW electrical capacity of technology 4 (coal)

1.25 GW electrical capacity of technology 5 (nuclear)

plus remaining heat to be supplied by CHP technologies 1 and 2 and HOB technology 9 in the ratio

1 GW_e: 1 GW_e : 1000 Mtherms

APPENDIX 6

Characteristics of power stations in CEGB merit order

After ordering all the CEGB's power stations into a de facto merit order, a numbe of conclusions may be drawn about the relationship between declared net capability, thermal efficiency and position in merit order. These relationships are plotted in Figures A6.1, A6.2, and A6.3. A fifteen point moving average is used in Figure A6.1 in order to reduce scatter and to make the trends more apparent.

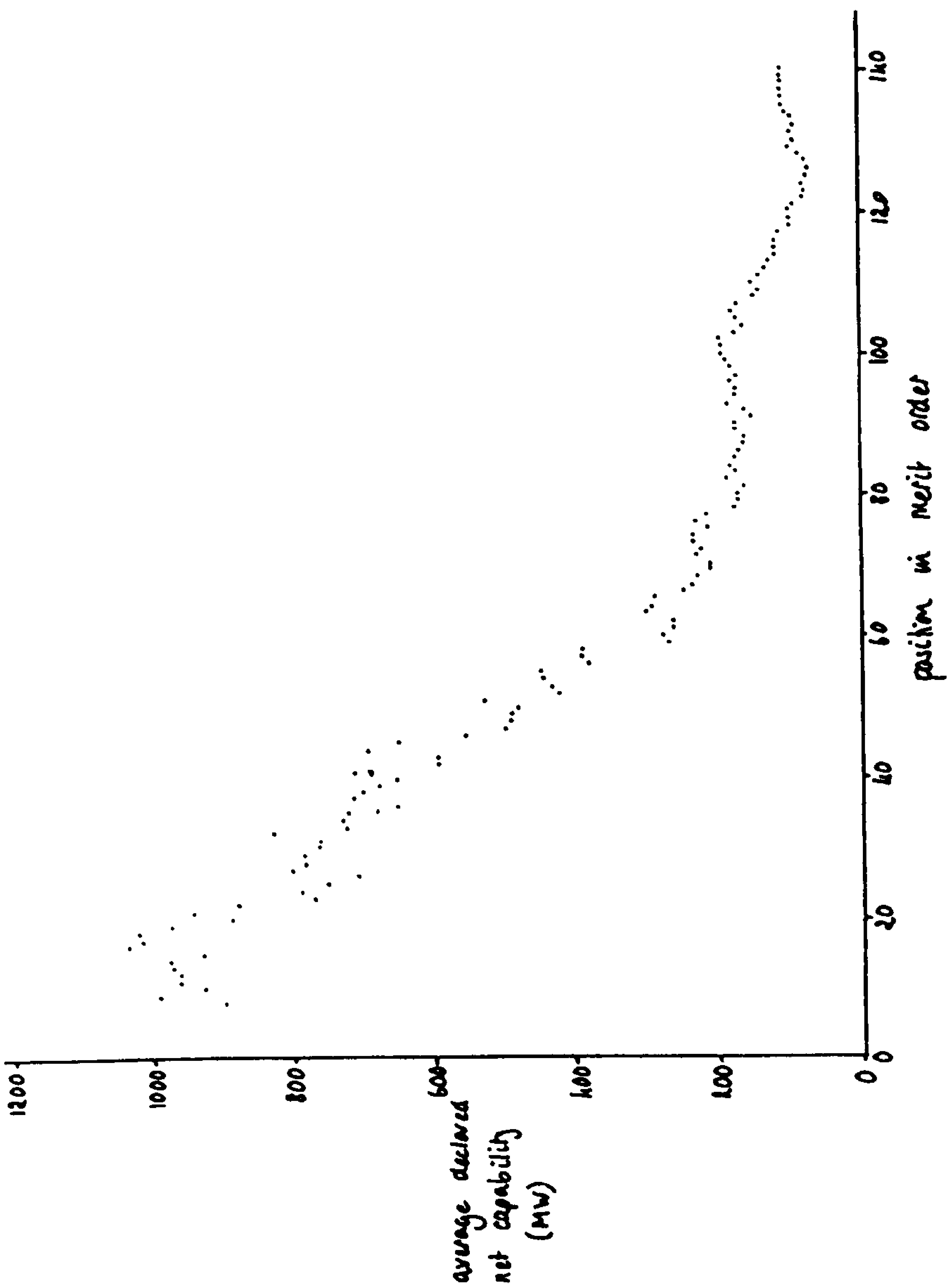


Figure A.6.1 Declared net capability as a function of merit order position

$$\text{average declared net capability} = \left[\sum_{n-7}^{n+7} d.n.c._{n}\right]/15$$

Figure A6.2 Efficiency vs merit order position (coal fired stations)

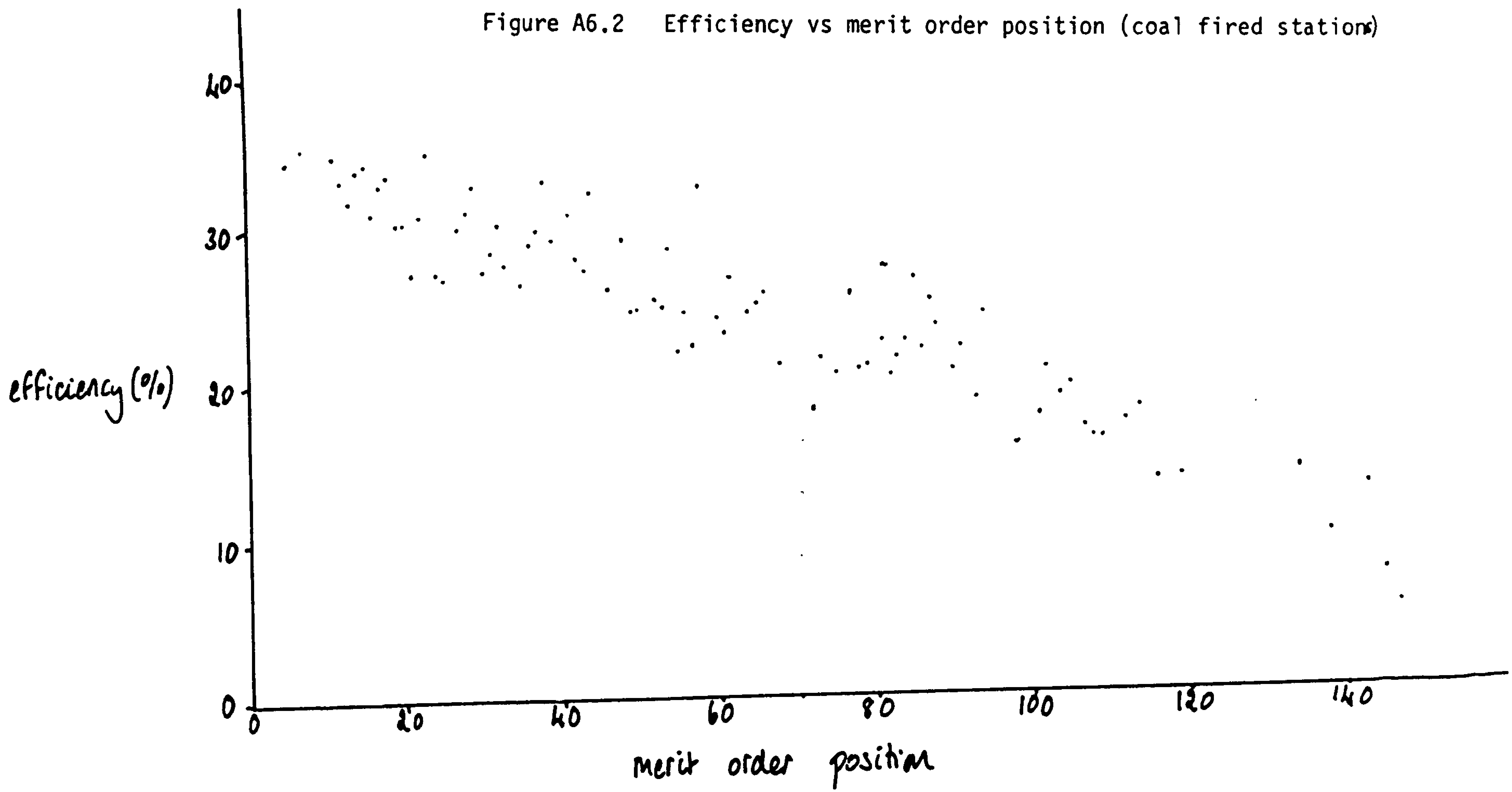
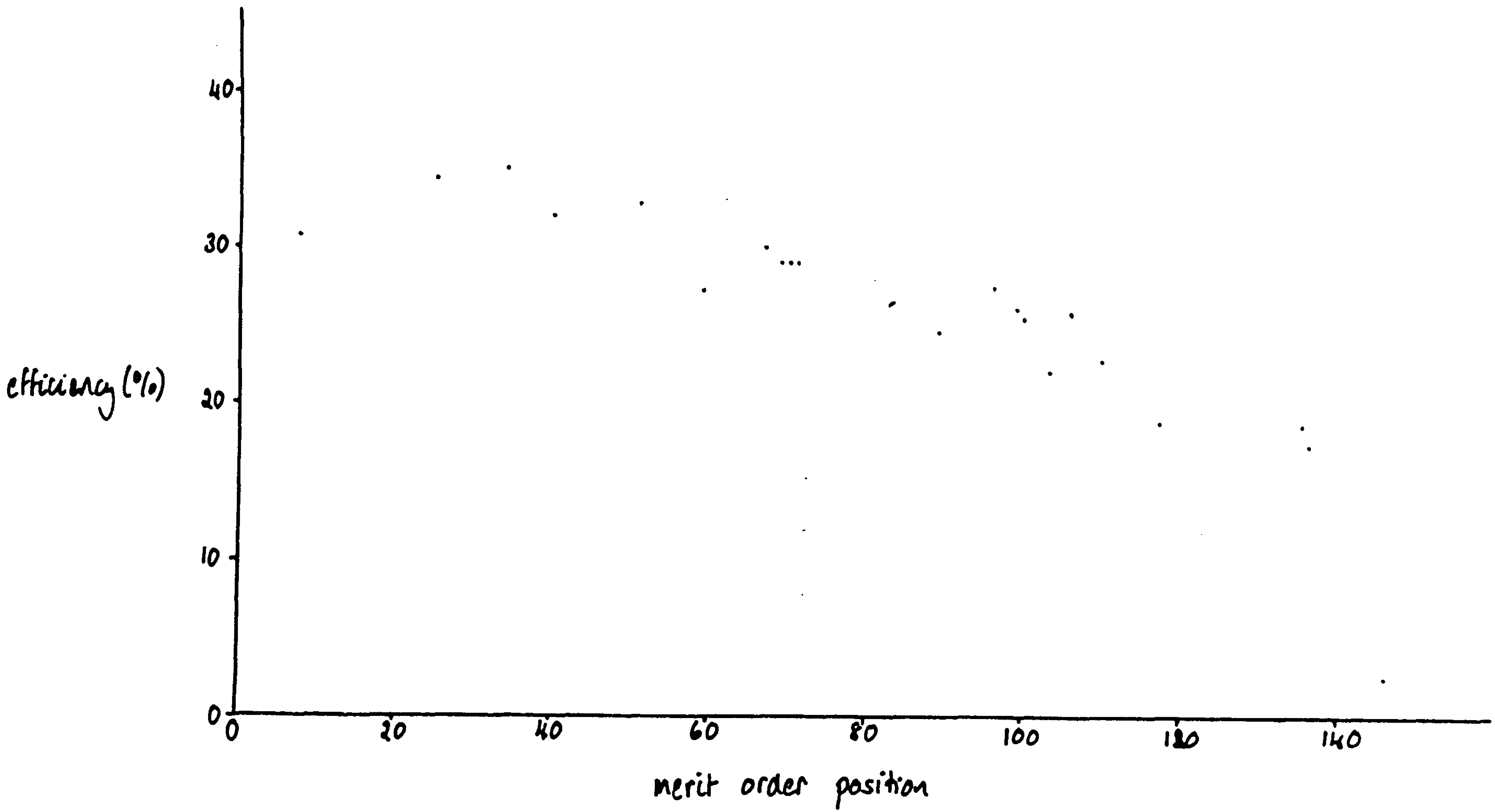


Figure A6.3 Efficiency vs merit order position (oil fired stations)



APPENDIX 7

Example of use of a simple linear model of electricity production

A small illustrative matrix can be shown in which the five electricity production processes (see Chapter 7) operate to produce an annual demand at constant load levels. In this hypothetical system there is no demand for gas, coal or oil other than for electricity production. There are 8 production processes producing coal, oil, gas and electricity. Four constraints are required for a unique vector of activity levels. The matrix is shown in Table A7.1 for which the processes and commodities are listed below.

Processes	Commodities
1 Coal production	1 Coal
2 Oil production	2 Oil
3 Gas production	3 Gas
4 Baseload I	4 Electricity
5 Baseload II	5 Constraint 1
6 Upper middle order	6 Constraint 2
7 Lower middle order	7 Constraint 3
8 Peak	8 Constraint 4

The matrix is shown in its 'starting position' ie only the first electricity process is unconstrained. All subsequent electricity production processes are constrained to an activity level of zero. In general it will be possible to anticipate which will be the marginal electricity process but for the sake of clarity, the full 'search procedure' will be illustrated here. The problem is to determine the activity levels of the production processes when the required electricity demand is 70,000 GWh (supplied at constant load).

commodity \ process	1	2	3	4	5	6	7	8	
1	100	0	0	-12.88	-16.63	-37.60	-33.74	-36.88	million tonnes
2	0	100	0	-619	-540	-6100	-6238	-14105	thousand tonnes
3	0	0	100	0	-167	-516	-60	-296	Mtherms
4	0	0	0	46835	39868	105879	101199	122737	GWh
5	0	0	0	0 (1)	1 (0)	0	0	0	
6	0	0	0	0	0 (0)	1 (0)	0	0	
7	0	0	0	0	0	0	1	0	
8	0	0	0	0	0	0	0	1	

Table A.7.1 Simple linear model of electricity production

Remembering that there is no demand for other fuels the final demand vector can be specified:

$$P = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \underline{70{,}000} \\ \hdashline 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

The corresponding vector of activity levels can be determined in the normal way

$$x = (A - B)^{-1}f$$

So that:

The first calculation yields an x vector:

$$\begin{pmatrix} .19 \\ 9.24 \\ 0 \\ 1.50 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

This vector is unacceptable since it gives an activity x_4, greater than one for the first electricity production process, implying a demand load factor greater than one in the load band 0 - 5.69 GW. This is responded to by altering the constraints in such a way that if there is to be no constraint on the process n then for the other constraints i

$$f_i = 1 \qquad i \leqslant n$$

$$f_i = 0 \qquad i > n$$

and

$$a_{ii} = 1 \quad i > n \text{ otherwise } a_{ij} = 0$$

$$a_{i,i-1} = 1 \quad i \leqslant n \text{ otherwise } a_{ij} = 0$$

By repeating the calculation using the amended constraint values shown in brackets in table A.7.1 with the new final demand vector

$$f = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 70,000 \\ \hdashline 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

a new vector of activities can be found, vis.

$$\begin{pmatrix} .225 \\ 9.33 \\ .970 \\ 1 \\ .581 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

This vector shows that the activity level of the first production process is 1, corresponding to 100% load factor of demand in that load band, and that the average load factor of demand in the second load band is 58.1%. This is an acceptable solution to the processes j $0 \leqslant x_j \leqslant 1$ of which only one $x_j \neq o, \neq 1$.

Consider now that the consequences of using the second constraint set to determine activity levels for a demand for 40,000 GWh. The corresponding vector of demand is now

$$f = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \underline{40{,}000} \\ 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

This yields an activity levels vector

$$x = \begin{pmatrix} .100 \\ 5.267 \\ -0.286 \\ 1 \\ -.171 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

The negative activity level value for the second electricity production process indicates that the unconstrained process needs to be 'moved to the left' and has in this case produced a further negative value in the vector. Restoration of the original constraint set gives the proper vector

$$x = \begin{pmatrix} .110 \\ 5.286 \\ 0 \\ .854 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

In practice it is not normally necessary to try more than once at determining the correct matrix since a fairly good starting point is provided by the 1977 constraint set. Only very radical alterations in demand or technology will require further searches for an acceptable activities vector.

APPENDIX 8

Demand for time-flagged electricity and heat

Electricity

Data for the level of detail required is sparse and incomplete. The approach taken was to disaggregate data on a 'best guess' basis and to check consistency both with data derived previously (see Chapter 5) and with other published data.

The starting points for deriving the data are the annual electricity demand data and the time flagged supply data.

Electricity consumers are:

coal mines	5090 GWh
coke ovens	210 GWh
oil refineries	920 GWh
iron and steel production	11390 GWh
other manufacturing and services	105830 GWh
transport	2930 GWh
final demand	39606 GWh
domestic heating	41108 GWh
commercial heating	13820 GWh

Electricity available (as derived in Chapter 7):

Time period 1	21382 GWh
Time period 2	24681 GWh
Time period 3	31945 GWh
Time period 4	12001 GWh
Time period 5	22827 GWh
Time period 6	27331 GWh

Time period 7	9212.6 GWh
Time period 8	15432 GWh
Time period 9	18454 GWh
Time period 10	13870 GWh
Time period 11	16943 GWh
Time period 12	19980 GWh

The data required is such that for each consuming sector, the total annual requirement is equal to the sector total and that the totals for each time period is equal to that given in the table above.

A number of assumptions are made using the time period labels derived from Baker's model (see Chapter 7). Values of i and j refer to the full scale model and are listed in full in Appendix 9.

Thus: assume that coal mining, coke production, oil refining and iron and steel production are year round processes, thus <u>for each time period</u>

$$b_{i,3} \quad (i = 101 \text{ to } 112) = 424.2 \text{ GWh}$$
$$b_{i,4} \quad (i = 101 \text{ to } 112) = 17.5 \text{ GWh}$$
$$b_{i,7} \quad (i = 101 \text{ to } 112) = 76.7 \text{ GWh}$$
$$b_{i,12} \quad (i = 101 \text{ to } 112) = 949.2 \text{ GWh}$$

assume that transport is 2-shift and non-seasonal

$$b_{i,16} \quad (i = 102, 103, 105, 106, 108, 109, 111, 112) = 366 \text{ GWh}$$

assume that Baker's model for off-peak domestic heating is correct

$$b_{101,21} = 19626 \text{ GWh}$$
$$b_{104,22} = 9237 \text{ GWh}$$
$$b_{107,23} = 988 \text{ GWh}$$
$$b_{110,24} = 11306 \text{ GWh}$$

assume that commercial space heating varies sinuoidally through the year and that water heating is constant throughout the year.

Water heating electricity assumption in each time period = 474 GWh.

assume that commercial heating is two-shift so

$b_{i,17}$ (i = 102, 103) = 2703 GWh

$b_{i,18}$ (i = 105, 106) = 1160 GWh

$b_{i,19}$ (i = 108, 109) = 746 GWh

$b_{i,20}$ (i = 110, 112) = 2295 GWh

assume that Baker's model gives the correct 'shape' for domestic 'non-space heating' demand and adjust accordingly and assume that this is the bulk of final demand. Thus

f_{101} = 1111 GWh

f_{102} = 4766 GWh

f_{103} = 7173 GWh

f_{104} = 820 GWh

f_{105} = 3521 GWh

f_{106} = 5299 GWh

f_{107} = 575 GWh

f_{108} = 2468 GWh

f_{109} = 3714 GWh

f_{110} = 864 GWh

f_{111} = 3710 GWh

f_{112} = 5583 GWh

Heat

Season heat demand is split on the basis of Baker's model of heating demand. Thus:

Commercial low grade heat:

Winter:	$a_{17,17}$ = 1388 Mtherms	$b_{17,14}$ = 725 Mtherms
Spring:	$a_{18,18}$ = 484 Mtherms	$b_{18,14}$ = 253 Mtherms
Summer:	$a_{19,19}$ = 245 Mtherms	$b_{19,14}$ = 128 Mtherms
Autumn:	$a_{20,20}$ = 1149 Mtherms	$b_{20,14}$ = 600 Mtherms
Final demand values:	f_{17} = 663 Mtherms,	f_{18} = 231 Mtherms
	f_{19} = 117 Mtherms,	f_{20} = 549 Mtherms

Domestic low grade heat:

Winter:	$a_{21,21}$ = 2617 Mtherms
Spring:	$a_{22,22}$ = 1096 Mtherms
Summer:	$a_{23,23}$ = 691 Mtherms
Autumn:	$a_{24,24}$ = 2222 Mtherms

Final demand values: since there is no intermediate demand for domestic low grade heat, final demand value correspond to the values above.

APPENDIX 9

Full specification of 112 x 112 matrices for full scale study.

The large size of the A-B Matrix makes presentation in Matrix format impractical. Data items are here presented in list form. This particular formulation is for CHP technology 1. Marginal sources of electricity production for each time period are those of 1977.

Explanatory note

'Products' with an asterisk denote constraining equations.

Products

1 Fuel gas
* 2 Gas production constraint
3 Coal
4 Coke
5 Crude oil
* 6 Crude oil production constraint
7 Refined fuel oil
* 8 Refined fuel oil production constraint
9 Refined non-fuel oil
10 Iron and steel
* 11 Iron and steel production constraint
12 Petrochemicals
*13 Petrochemicals production constraint
14 Other goods and services
*15 Imports constraint
16 Transport
17 Commercial low grade heat : winter
18 Commercial low grade heat : spring
19 Commercial low grade heat : summer
20 Commercial low grade heat : autumn
21 Domestic low grade heat : winter
22 Domestic low grade heat : spring
23 Domestic low grade heat : summer
24 Domestic low grade heat : autumn
25 Low grade heat for transmission
26 Low grade heat for transmission
27 Low grade heat for transmission
28 Low grade heat for transmission
*29 HOB use; constraint 1
*30 HOB use; constraint 2
*31 HOB use; constraint 3
*32 HOB use; constraint 4
*33 District heating commercial market share; constraint 1
*34 District heating commercial market share; constraint 2
*35 District heating commercial market share; constraint 3
*36 District heating commercial market share; constraint 4
*37 District heating domestic market share; constraint 1
*38 District heating domestic market share; constraint 2
*39 District heating domestic market share; constraint 3
*40 District heating domestic market share; constraint 4
41 Electricity for transmission; time period 1
42 Electricity for transmission; time period 2
43 Electricity for transmission; time period 3
44 Electricity for transmission; time period 4
45 Electricity for transmission; time period 5
46 Electricity for transmission; time period 6
47 Electricity for transmission; time period 7
48 Electricity for transmission; time period 8
49 Electricity for transmission; time period 9
50 Electricity for transmission; time period 10
51 Electricity for transmission; time period 11
52 Electricity for transmission; time period 12
*53 Electricity production; time period 1, load band constraint 1
*54 time period 2, load band constraint 1
*55 time period 3, load band constraint 1
*56 time period 4, load band constraint 1
*57 time period 5, load band constraint 1
*58 time period 6, load band constraint 1
*59 time period 7, load band constraint 1
*60 time period 8, load band constraint 1
*61 time period 9, load band constraint 1
*62 time period 10, load band constraint 1
*63 time period 11, load band constraint 1
*64 time period 12, load band constraint 1
*65 Electricity production; time period 1, load band constraint 2
*66 time period 2, load band constraint 2
*67 time period 3, load band constraint 2

```
*68 Electricity production; time period  4, load band constraint 2
*69                         time period  5, load band constraint 2
*70                         time period  6, load band constraint 2
*71                         time period  7, load band constraint 2
*72                         time period  8, load band constraint 2
*73                         time period  9, load band constraint 2
*74                         time period 10, load band constraint 2
*75                         time period 11, load band constraint 2
*76                         time period 12, load band constraint 2
*77 Electricity production; time period  1, load band constraint 3
*78                         time period  2, load band constraint 3
*79                         time period  3, load band constraint 3
*80                         time period  4, load band constraint 3
*81                         time period  5, load band constraint 3
*82                         time period  6, load band constraint 3
*83                         time period  7, load band constraint 3
*84                         time period  8, load band constraint 3
*85                         time period  9, load band constraint 3
*86                         time period 10, load band constraint 3
*87                         time period 11, load band constraint 3
*88                         time period 12, load band constraint 3
*89 Electricity production; time period  1, load band constraint 4
*90                         time period  2, load band constraint 4
*91                         time period  3, load band constraint 4
*92                         time period  4, load band constraint 4
*93                         time period  5, load band constraint 4
*94                         time period  6, load band constraint 4
*95                         time period  7, load band constraint 4
*96                         time period  8, load band constraint 4
*97                         time period  9, load band constraint 4
*98                         time period 10, load band constraint 4
*99                         time period 11, load band constraint 4
*100                        time period 12, load band constraint 4
 101 Electricity transmission; time period  1
 102                           time period  2
 103                           time period  3
 104                           time period  4
 105                           time period  5
 106                           time period  6
 107                           time period  7
 108                           time period  8
 109                           time period  9
 110                           time period 10
 111                           time period 11
 112                           time period 12
```

Units of measurement for products

1	Mtherms
3	Million tonnes
4	Million tonnes
5	Thousand tonnes
7	Thousand tonnes
9	Thousand tonnes
10	1977 production level
12	Thousand tonnes
14	1977 production level
16	1977 production level
17	Mtherms
18	Mtherms
19	Mtherms
20	Mtherms
21	Mtherms
22	Mtherms
23	Mtherms
24	Mtherms
25	Mtherms
26	Mtherms
27	Mtherms
28	Mtherms
41	GWh
42	GWh
43	GWh
44	GWh
45	GWh
46	GWh
47	GWh
48	GWh
49	GWh
50	GWh
51	GWh
52	GWh
101	GWh
102	GWh
103	GWh
104	GWh
105	GWh
106	GWh
107	GWh
108	GWh
109	GWh
110	GWh
111	GWh
112	GWh

Processes

1 North Sea gas production
2 Synthetic natural gas production
3 Coal mining
4 Coke production
5 Crude oil production (North Sea)
6 Crude oil importing
7 Oil refining
8 Refined fuel oil importing
9 Other refined oil importing
10 Iron and steel production
11 Iron and steel importing
12 Petrochemical production
13 Petrochemical importing
14 Other manufacturing and services
15 Other importing
16 Transport
17 Heating for commercial premises : winter
18 Heating for commercial premises : spring
19 Heating for commercial premises : summer
20 Heating for commercial premises : autumn
21 Heating for domestic premises : winter
22 Heating for domestic premises : spring
23 Heating for domestic premises : summer
24 Heating for domestic premises : autumn
25 CHP : winter
26 CHP : spring
27 CHP : summer
28 CHP : autumn
29 HOBs : winter
30 HOBs : spring
31 HOBs : summer
32 HOBs : autumn
33 heat transmission and distribution to commercial premises : winter
34 heat transmission and distribution to commercial premises : spring
35 heat transmission and distribution to commercial premises : summer
36 heat transmission and distribution to commercial premises : autumn
37 heat transmission and distribution to domestic premises : winter
38 heat transmission and distribution to domestic premises : spring
39 heat transmission and distribution to domestic premises : summer
40 heat transmission and distribution to domestic premises : autumn
41 Electricity production : baseload I; time period 1
42 time period 2
43 time period 3
44 time period 4
45 time period 5
46 time period 6
47 time period 7
48 time period 8
49 time period 9
50 time period 10
51 time period 11
52 time period 12
53 Electricity production : baseload II; time period 1
54 time period 2
55 time period 3
56 time period 4
57 time period 5
58 time period 6
59 time period 7
60 time period 8
61 time period 9
62 time period 10
63 time period 11
64 time period 12
65 Electricity production : Low load, middle order; time period 1
66 time period 2
67 time period 3
68 time period 4
69 time period 5
70 time period 6
71 time period 7

72	Electricity production : Low load, middle order;	time period 8
73		time period 9
74		time period 10
75		time period 11
76		time period 12
77	Electricity production : High load, middle order;	time period 1
78		time period 2
79		time period 3
80		time period 4
81		time period 5
82		time period 6
83		time period 7
84		time period 8
85		time period 9
86		time period 10
87		time period 11
88		time period 12
89	Electricity production : peak;	time period 1
90		time period 2
91		time period 3
92		time period 4
93		time period 5
94		time period 6
95		time period 7
96		time period 8
97		time period 9
98		time period 10
99		time period 11
100		time period 12
101	Electricity transmission :	time period 1
102		time period 2
103		time period 3
104		time period 4
105		time period 5
106		time period 6
107		time period 7
108		time period 8
109		time period 9
110		time period 10
111		time period 11
112		time period 12

1977 vector of process activity levels

j	x_j	j	x_j
1	1	57	1
2	0	58	1
3	1	59	1
4	1	60	1
5	1	61	1
6	1	62	1
7	1	63	1
8	1	64	1
9	0	65	1
10	1	66	1
11	1	67	1
12	1	68	0.5130
13	1	69	1
14	1	70	1
15	1	71	0.1969
16	1	72	0.9018
17	1	73	1
18	1	74	0.7248
19	1	75	1
20	1	76	1
21	1	77	0.6028
22	1	78	0.9940
23	1	79	1
24	1	80	0
25	0	81	0.7742
26	0	82	1
27	0	83	0
28	0	84	0
29	0	85	0.2556
30	0	86	0
31	0	87	0.0764
32	0	88	0.4366
33	0	89	0
34	0	90	0
35	0	91	0.7052
36	0	92	0
37	0	93	0
38	0	94	0.2542
39	0	95	0
40	0	96	0
41	1	97	0
42	1	98	0
43	1	99	0
44	1	100	0
45	1	101	29.29
46	1	102	33.81
47	1	103	43.76
48	1	104	16.44
49	1	105	31.27
50	1	106	37.44
51	1	107	12.62
52	1	108	21.14
53	1	109	25.28
54	1	110	19.00
55	1	111	23.21
56	1	112	27.37

Specification of full scale (112 x 112) matrix

A. By process

j	i	$a_{ij} - b_{ij}$
1	1	15449
1	7	704
2	1	1000
2	2	1
2	3	-6.15
3	3	124.5
3	101	-424.2
3	102	-424.2
3	103	-424.2
3	104	-424.2
3	105	-424.2
3	106	-424.2
3	107	-424.2
3	108	-424.2
3	109	-424.2
3	110	-424.2
3	112	-424.2
3	112	-424.2
4	1	406
4	3	-20.6
4	4	13.6
4	101	-17.5
4	102	-17.5
4	103	-17.5
4	104	-17.5
4	105	-17.5
4	106	-17.5
4	107	-17.5
4	108	-17.5
4	109	-17.5
4	110	-17.5
4	111	-17.5
4	112	-17.5
5	5	37540
5	6	-1
6	5	70697
6	6	1
7	1	998
7	5	-93614
7	7	50563
7	8	1
7	9	33338
7	101	-76.7
7	102	-76.7
7	103	-76.7
7	104	-76.7
7	105	-76.7
7	106	-76.7
7	107	-76.7
7	108	-76.7
7	109	-76.7
7	110	-76.7
7	111	-76.7
7	112	-76.7
8	7	13050

j	i	$a_{ij} - b_{ij}$
9	9	1000
10	1	-153
10	7	-5747
10	10	0.38
10	11	-1
11	10	0.62
11	11	1
12	1	-688
12	3	-0.2
12	4	-8
12	7	-2940
12	12	20411
12	13	1
12	101	-949.2
12	102	-949.2
12	103	-949.2
12	104	-949.2
12	105	-949.2
12	106	-949.2
12	107	-949.2
12	108	-949.2
12	109	-949.2
12	110	-949.2
12	111	-949.2
12	112	-949.2
13	12	3719
13	13	-1
14	1	-6410
14	3	-7.5
14	7	-19347
14	9	-3491
14	10	-0.23
14	12	-20411
14	14	0.7
14	15	-1
14	16	-1
14	17	-725
14	18	-253
14	19	-128
14	20	-600
14	102	-13618
14	103	-17880
14	104	-421
14	105	-14414
14	106	-16822
14	107	-5463
14	108	-5463
14	109	-10745
14	110	-205
14	111	-8044
14	112	-9073
15	14	0.3
15	15	1
16	3	-0.1
16	9	-13428

j	i	$a_{ij} - b_{ij}$
16	16	1
16	102	-366
16	103	-366
16	105	-366
16	106	-366
16	108	-366
16	109	-366
16	111	-366
16	112	-366
17	1	-489
17	3	-0.8
17	4	-0.3
17	7	-2585
17	17	1388
17	102	-2703
17	103	-2703
18	1	-171
18	3	-0.3
18	4	-0.1
18	7	-901
18	18	484
18	105	-1160
18	106	-1160
19	1	-86
19	3	-0.2
19	7	-456
19	19	245
19	108	-746
19	109	-746
20	1	-405
20	3	-0.7
20	4	-0.3
20	7	-2139
20	20	1149
20	111	-2295
20	112	-2295
21	1	-2100
21	3	-4.4
21	4	-1.5
21	7	-1310
21	21	2617
21	101	-19626
22	1	-876
22	3	-1.8
22	4	-0.6
22	7	-547
22	22	1096
22	104	-9237
23	1	-552
23	3	-1.2
23	4	-0.4
23	7	-345
23	23	691
23	107	-988

j	i	$a_{ij} - b_{ij}$
24	1	-1776
24	3	-3.7
24	4	-1.2
24	7	-1108
24	24	2222
24	110	-11306
25	3	-1.2
25	25	179
25	41	730
25	42	730
25	43	730
26	3	-1.2
26	26	179
26	44	
26	45	
26	46	
27	3	-1.2
27	27	179
27	47	730
27	48	730
27	49	730
28	3	-1.2
28	28	179
28	50	730
28	51	730
28	52	730
29	3	0.125
29	25	250
29	29	1
30	3	-0.125
30	26	250
30	30	1
31	3	-0.126
31	27	250
31	31	1
32	3	-0.125
32	28	250
32	32	1
33	17	1388
33	25	-1542
33	33	1
34	18	484
34	26	-538
34	34	1
35	19	245
35	27	-272
35	35	1

j	i	$a_{ij} - b_{ij}$
36	20	1149
36	28	-1277
36	36	1
37	21	2617
37	25	-2908
37	37	1
38	22	1096
38	26	-1218
38	38	1
39	23	691
39	27	-768
39	39	1
40	24	2222
40	28	-2469
40	40	1
41	3	-1.07
41	7	-51.58
41	41	4152.9
41	53	1
42	3	-1.07
42	7	-51.58
42	42	4152.9
42	54	1
43	3	-1.07
43	7	-51.58
43	43	4152.9
43	55	1
44	3	-1.07
44	7	-51.58
44	44	4152.9
44	56	1
45	3	-1.07
45	7	-51.58
45	45	4152.9
45	57	1
46	3	-1.07
46	7	-51.58
46	46	4152.9
46	58	1
47	3	-1.07
47	7	-51.58
47	47	4152.9
47	59	1
48	2	-1.07
48	7	-51.58
48	48	4152.9
48	60	1
49	3	-1.07
49	7	-51.58
49	49	4152.9
49	61	1
50	3	-1.07
50	7	-51.58
50	50	4152.9
50	62	1
51	3	-1.07
51	7	-51.58
51	51	4152.9
51	63	1
52	3	-1.07
52	7	-51.58
52	52	4152.9
52	64	1
53	1	-13.92
53	3	-1.39
53	7	-45
53	41	3322.3
53	65	1
54	1	-13.92
54	3	-1.39
54	7	-45
54	42	3322.3
54	66	1
55	1	-13.92
55	3	-1.39
55	7	-45
55	43	3322.3
55	67	1
56	1	-13.92
56	3	-1.39
56	7	-45
56	44	3322.3
56	68	1
57	1	-13.92
57	3	-1.39
57	7	-45
57	45	3322.3
57	69	1
58	1	-13.92
58	3	-1.39
58	7	-45
58	46	3322.2
58	70	1
59	1	-13.92
59	3	-1.39
59	7	-45
59	47	3322.3
59	71	1
60	1	-13.92
60	3	-1.39
60	7	-45
60	48	3322.3
60	72	1
61	1	-13.92
61	3	-1.39
61	7	-45
61	49	3322.3
61	73	1
62	1	-13.92
62	3	-1.39
62	7	-45
62	50	3322.3
62	74	1

355

j	i	$a_{ij} - b_{ij}$
63	1	-13.92
63	3	-1.39
63	7	-45
63	51	3322.3
63	75	1
64	1	-13.92
64	3	-1.39
64	7	-45
64	52	3322.3
64	76	1
65	1	-43
65	3	-3.13
65	7	-508.3
65	41	8823.2
65	77	1
66	1	-43
66	3	-3.13
66	7	-508.3
66	42	8823.2
66	78	1
67	1	-43
67	3	-3.13
67	7	-508.3
67	43	8823.2
67	79	1
68	1	-43
68	3	-3.13
68	7	-508.3
68	44	8823.3
69	1	-43
69	3	-3.13
69	7	-508.3
69	45	8823.2
69	81	1
70	1	-43
70	3	-3.13
70	7	-508.3
70	46	8823.2
70	82	1
71	1	-43
71	3	-3.13
71	7	-508.3
71	47	8823.2
72	1	-43
72	3	-3.13
72	7	-508.3
72	48	8823.2
73	1	-43
73	3	-3.13
73	7	-508.3
73	49	8823.2
73	85	1
74	1	-43
74	3	-3.13
74	7	-508.3
74	50	8823.2

j	i	$a_{ij} - b_{ij}$
75	1	-43
75	3	-3.13
75	7	-508.3
75	51	8823.2
75	87	1
76	1	-43
76	3	-3.13
76	7	-508.3
76	52	8823.2
76	88	1
77	1	-5
77	3	-2.81
77	7	-519.8
77	41	8433.1
78	1	-5
78	3	-2.81
78	7	-519.8
78	42	8433.1
79	1	-5
79	3	-2.81
79	7	-519.8
79	43	8433.1
79	91	1
80	1	-5
80	3	-2.81
80	7	-519.8
80	44	8433.1
80	80	1
81	1	-5
81	3	-2.81
81	7	-519.8
81	45	8433.1
82	1	-5
82	3	-2.81
82	7	-519.8
82	46	8433.1
82	94	1
83	1	-5
83	3	-2.81
83	7	-519.8
83	47	8433.1
83	83	1
84	1	-5
84	3	-2.81
84	7	-519.8
84	48	8433.1
84	84	1
85	1	-5
85	3	-2.81
85	7	-519.8
85	49	8433.1
86	1	-5
86	3	-2.81
86	7	-519.8
86	50	8433.1
86	86	1

j	i	$a_{ij} - b_{ij}$
87	1	-5
87	3	-2.81
87	7	-519.8
87	51	8433.1
88	1	-5
88	3	-2.81
88	7	-519.8
88	52	8433.1
89	1	-24.67
89	3	-3.07
89	7	-1175.4
89	41	10228.1
89	89	1
90	1	24.67
90	3	-3.07
90	7	-1175.4
90	42	10228.1
90	90	1
91	1	-24.67
91	3	-3.07
91	7	-1175.4
91	43	10228.1
92	1	-24.67
92	3	-3.07
92	7	-1175.4
92	44	10228.1
93	1	-24.67
93	3	-3.07
93	7	-1175.4
93	45	10228.1
93	93	1
94	1	-24.67
94	3	-3.07
94	7	-1175.4
94	46	10228.1
95	1	-24.67
95	3	-3.07
95	7	-1175.4
95	47	10228.1
95	95	1
96	1	-24.67
96	3	-3.07
96	7	-1175.4
96	48	10228.1
96	96	1
97	1	-24.67
97	3	-3.07
97	7	-1175.4
97	49	10228.1
97	97	1
98	1	-24.67
98	3	-3.07
98	7	-1175.4
98	50	10228.1
98	98	1

j	i	$a_{ij} - b_{ij}$
99	1	-24.67
99	3	-3.07
99	7	-1175.4
99	51	10228.1
99	99	1
100	1	-24.67
100	3	-3.07
100	7	-1175.4
100	52	10228.1
100	100	1
101	41	-730
101	101	730
102	42	-730
102	102	730
103	43	-730
103	103	730
104	44	-730
104	104	730
105	45	-730
105	105	730
106	46	-730
106	106	730
107	47	-730
107	107	730
108	48	-730
108	108	730
109	49	-730
109	108	730
110	50	-730
110	109	730
111	51	-730
111	110	730
112	52	-730
112	112	730

Specification of full scale (112 x 112) matrix

B By product

i	j	$a_{ij} - b_{ij}$
1	1	15449
1	2	1000
1	4	406
1	7	998
1	10	-153
1	12	-688
1	14	-6410
1	17	-489
1	18	-171
1	19	-86
1	20	-405
1	21	-2100
1	22	-876
1	23	-552
1	24	-1776
1	53	-13.92
1	54	-13.92
1	55	-13.92
1	56	-13.92
1	57	-13.92
1	58	-13.92
1	59	-13.92
1	60	-13.92
1	61	-13.92
1	62	-13.92
1	63	-13.92
1	64	-13.92
1	65	-43
1	66	-43
1	67	-43
1	68	-43
1	69	-43
1	70	-43
1	71	-43
1	72	-43
1	73	-43
1	74	-43
1	75	-43
1	76	-43
1	77	-5
1	78	-5
1	79	-5
1	80	-5
1	81	-5
1	82	-5
1	83	-5
1	84	-5
1	85	-5
1	86	-5
1	87	-5
1	88	-5
1	89	-24.67
1	90	-24.67
1	91	-24.67
1	92	-24.67
1	93	-24.67
1	94	-24.67
1	95	-24.67
1	96	-24.67
1	97	-24.67
1	98	-24.67
1	99	-24.67
1	100	-24.67
2	2	1

i	j	$a_{ij} - b_{ij}$
3	2	-6.15
3	3	124.5
3	4	-20.6
3	12	-0.2
3	14	-7.5
3	16	-0.1
3	17	-0.8
3	18	-0.3
3	19	-0.2
3	20	-0.7
3	21	-4.4
3	22	-1.8
3	23	-1.2
3	24	-3.7
3	25	-1.2
3	26	-1.2
3	27	-1.2
3	28	-1.2
3	29	-0.125
3	30	-0.125
3	31	-0.125
3	32	-0.125
3	41	-1.07
3	42	-1.07
3	43	-1.07
3	44	-1.07
3	45	-1.07
3	46	-1.07
3	47	-1.07
3	48	-1.07
3	49	-1.07
3	50	-1.07
3	51	-1.07
3	52	-1.07
3	53	-1.39
3	54	-1.39
3	55	-1.39
3	56	-1.39
3	57	-1.39
3	58	-1.39
3	59	-1.39
3	60	-1.39
3	61	-1.39
3	62	-1.39
3	63	-1.39
3	64	-1.39
3	65	-3.13
3	66	-3.13
3	67	-3.13
3	68	-3.13
3	69	-3.13
3	70	-3.13
3	71	-3.13
3	72	-3.13
3	73	-3.13
3	74	-3.13
3	75	-3.13
3	76	-3.13
3	77	-2.81
3	78	-2.81
3	79	-2.81
3	80	-2.81
3	81	-2.81
3	82	-2.81

i	j	$a_{ij} - b_{ij}$
3	83	-2.81
3	84	-2.81
3	85	-2.81
3	86	-2.81
3	87	-2.81
3	88	-2.81
3	89	-3.07
3	90	-3.07
3	91	-3.07
3	92	-3.07
3	93	-3.07
3	94	-3.07
3	95	-3.07
3	96	-3.07
3	97	-3.07
3	98	-3.07
3	99	-3.07
3	100	-3.07
4	4	13.6
4	12	-8
4	17	-0.3
4	18	-0.1
4	20	-0.3
4	21	-1.5
4	22	-0.6
4	23	-0.4
4	24	-1.2
5	5	37540
5	6	70697
5	7	-93614
6	5	-1
6	6	1
7	1	704
7	7	50563
7	8	13050
7	10	-5747
7	12	-2940
7	14	-19347
7	17	-2585
7	18	-901
7	19	-456
7	20	-2139
7	21	-1310
7	22	-547
7	23	-345
7	24	-1108
7	41	-51.58
7	42	-51.58
7	43	-51,58
7	44	-51.58
7	45	-51.58
7	46	-51.58
7	47	-51.58
7	48	-51.58
7	49	-51.58
7	50	-51.58
7	52	-51.58
7	53	-45
7	54	-45
7	55	-45
7	56	-45
7	57	-45
7	58	-45
7	59	-45
7	60	-45

i	i	$a_{ij} - b_{ij}$
7	61	-45
7	62	-45
7	63	-45
7	64	-45
7	65	-508.3
7	66	-508.3
7	67	-508.3
7	68	-508.3
7	69	-508.3
7	70	-508.3
7	71	-508.3
7	72	-508.3
7	73	-508.3
7	74	-508.3
7	75	-508.3
7	76	-508.3
7	77	-519.8
7	78	-519.8
7	79	-519.8
7	80	-519.8
7	81	-519.8
7	82	-519.8
7	83	-519.8
7	84	-519.8
7	85	-519.8
7	86	-519.8
7	87	-519.8
7	88	-519.8
7	89	-1175.4
7	90	-1175.4
7	91	-1175.4
7	92	-1175.4
7	93	-1175.4
7	94	-1175.4
7	95	-1175.4
7	96	-1175.4
7	97	-1175.4
7	98	-1175.4
7	99	-1175.4
7	100	-1175.4
8	7	1
9	7	33338
9	9	1000
9	14	-3491
9	16	-13428
10	10	0.38
10	11	0.62
10	14	-0.23
11	10	-1
11	11	1
12	12	20411
12	13	3719
12	14	-20411
13	12	1
13	13	-1
14	14	0.7
14	15	0.3
15	14	-1
15	15	1
16	14	-1

i	j	$a_{ij} - b_{ij}$
16	16	-1
17	14	-725
17	17	1388
18	14	-253
18	18	484
19	14	-128
19	19	245
20	14	-600
20	20	1149
21	21	2617
22	22	1096
23	23	691
24	24	2222
25	25	179
25	29	250
25	33	-1542
25	37	-2908
26	26	179
26	30	250
26	34	-538
26	38	-1218
27	27	179
27	31	250
27	35	-272
27	39	-768
28	28	179
28	32	250
28	36	-1277
28	40	-2469
29	29	1
30	30	1
31	31	1
32	32	1
33	33	1
34	34	1
35	35	1
36	36	1
37	37	1
38	38	1
39	39	1
40	40	1

i	j	$a_{ij} - b_{ij}$
41	25	730
41	41	4152.9
41	53	3322.3
41	65	8823.2
41	77	8433.1
41	89	10228.1
41	101	-730
42	25	730
42	42	4152.9
42	54	3322.3
42	66	8823.2
42	70	8433.1
42	90	10228.1
42	102	-730
43	25	730
43	43	4152.9
43	55	3322.3
43	67	8823.2
43	79	8433.1
43	91	10228.1
43	103	-730
44	26	730
44	44	4152.9
44	56	3322.3
44	68	8823.2
44	80	8433.1
44	92	10228.1
44	104	-730
45	26	730
45	45	4152.9
45	57	3322.3
45	69	8823.2
45	81	8433.1
45	93	10228.1
45	105	-730
[illegible]	26	730
46	46	4152.9
46	58	3322.3
46	70	8823.3
46	82	8433.1
46	94	10228.1
46	106	-730
47	27	730
47	47	4152.9
47	59	3322.3
47	71	8823.3
47	83	8433.1
47	95	10228.1
47	107	-730
48	27	730
48	48	4152.9
48	60	3322.3
48	72	8823.3
48	84	8433.1
48	96	10228.1
48	108	-730

i	j	$a_{ij} - b_{ij}$
49	27	730
49	49	4152.9
49	61	3322.3
49	73	8823.3
49	85	8433.1
49	97	10228.1
49	109	-730
50	28	730
50	50	4152.9
50	62	3322.3
50	74	8823.3
50	86	8433.1
50	98	10228.1
50	110	-730
51	28	730
51	51	4152.9
51	63	3322.3
51	75	8823.3
51	87	8433.1
51	99	10228.1
51	111	-730
52	28	730
52	52	4152.9
52	64	3322.3
52	76	8823.3
52	88	8433.1
52	100	10228.1
52	112	-730
53	41	1
54	42	1
55	43	1
56	44	1
57	45	1
58	46	1
59	47	1
60	48	1
61	49	1
62	50	1
63	51	1
64	52	1
65	53	1
66	54	1
67	55	1
68	56	1
69	57	1
70	58	1
71	59	1
72	60	1

i	j	$a_{ij} - b_{ij}$
73	61	1
74	62	1
75	63	1
76	64	1
77	65	1
78	66	1
79	67	1
80	68	1
81	69	1
82	70	1
83	71	1
84	72	1
85	73	1
86	86	1
87	75	1
88	76	1
89	89	1
90	90	1
91	79	1
92	92	1
93	93	1
94	82	1
95	95	1
96	96	1
97	97	1
98	98	1
99	99	1
100	100	1
101	3	-424.2
101	4	-17.5
101	7	-76.7
101	12	-949.2
101	21	-19626
101	101	730
102	3	-424.2
102	4	-17.5
102	7	-76.7
102	12	-949.2
102	14	-13618
102	16	-366
102	17	-2703
102	102	730

i	j	$a_{ij} - b_{ij}$	i	j	$a_{ij} - b_{ij}$
103	3	-424.2	108	2	-424.2
103	4	-17.5	108	4	-17.5
103	7	-76.7	108	7	-76.7
103	12	-949.2	108	12	-949.2
103	14	-17880	108	14	-9175
103	16	-366	108	16	-366
103	17	-2703	108	19	-746
103	103	730	108	108	730
104	3	-424.2	109	2	-424.2
104	4	-17.5	109	4	-17.5
104	7	-76.7	109	7	-76.7
104	12	-949.2	109	12	-949.2
104	14	-421	109	14	-10745
104	22	-9237	109	16	-366
104	104	730	109	19	-746
			109	109	730
105	2	-424.2	110	2	-424.2
105	4	-17.5	110	4	-17.5
105	7	-76.7	110	7	-76.7
105	12	-949.2	110	12	-949.2
105	14	-14414	110	14	-205
105	16	-366	110	24	-11306
105	18	-1160	110	110	730
105	105	730			
106	2	-424.2	111	2	-424.2
106	4	-17.5	111	4	-17.5
106	7	-76.7	111	7	-76.7
106	12	-949.2	111	12	-949.2
106	14	-16822	111	14	-8044
106	16	-366	111	16	-366
106	18	-1160	111	20	-2295
106	106	730	111	111	730
107	2	-424.2	112	2	-424.2
107	4	-17.5	112	4	-17.5
107	7	-76.7	112	7	-76.7
107	12	-949.2	112	12	-949.2
107	14	-5463	112	14	-9073
107	23	-988	112	16	-366
107	107	730	112	20	-2295
			112	112	730

Final demand vector (f) and Total availability vector (q)

i	f_i	q_i	i	f_i	q_i
1	2486	16853	57	1	1
2	0	0	58	1	1
3	3.74	124.5	59	1	1
4	1.2	13.6	60	1	1
5	14623	108237	61	1	1
6	0	1	62	1	1
7	16680	63317	63	1	1
8	1	1	64	1	1
9	16419	33338	65	1	1
10	0.77	1	66	1	1
11	0	1	67	1	1
12	3719	24130	68	1	1
13	0	1	69	1	1
14	1	1	70	1	1
15	0	1	71	1	1
16	0	1	72	1	1
17	663	1388	73	1	1
18	231	484	74	1	1
19	117	245	75	1	1
20	549	1149	76	1	1
21	2617	2617	77	1	1
22	1096	1096	78	1	1
23	691	691	79	1	1
24	2222	2222	80	0	0
25	0	0	81	1	1
26	0	0	82	1	1
27	0	0	83	0	0
28	0	0	84	0	0
29	0	0	85	1	1
30	0	0	86	0	0
31	0	0	87	1	1
32	0	0	88	1	1
33	0	0	89	0	0
34	0	0	90	0	0
35	0	0	91	1	1
36	0	0	92	0	0
37	0	0	93	0	0
38	0	0	94	1	1
39	0	0	95	0	0
40	0	0	96	0	0
41	0	21382	97	0	0
42	0	24681	98	0	0
43	0	31945	99	0	0
44	0	12001	100	0	0
45	0	22827	101	338	21432
46	0	27331	102	4766	22416
47	0	9212.6	103	7173	29115
48	0	15432	104	820	11946
49	0	18454	105	3521	20454
50	0	13870	106	5299	24640
51	0	16943	107	575	8493.6
52	0	19980	108	2468	13749
53	1	1	109	3714	16565
54	1	1	110	864	13843
55	1	1	111	3710	15409
56	1	1	112	5583	18311

APPENDIX 10 : Fuel savings from using CHP

Fuel savings which arise from the use of CHP are at one level very simple to estimate and at another very complex. The purpose of this appendix is simply to point out the potential pitfalls of simple truisms such as 'CHP could save X mtce per year'.

Taking 100 units of fossil fuel as the basis of comparison, the conventional heater in figure A 10.1 with a thermal efficiency of η_h per cent will produce η_h units of heat; a power station with an overall thermal efficiency of η_e per cent will produce η_e units of electricity. Alternatively, the 100 units of fuel could be used in a CHP station where it can be shown (Appendix 2 and A.10.1) that $\eta_e/(1 + RZ)$ units of electricity and $\eta_e R/(1 + RZ)$ units of heat will be produced (Z is defined here on a 'constant fuel input' basis).

At this point it is tempting to compare the efficiency of the CHP station with that of the power station:

$$\frac{\text{energy output from CHP station}}{\text{energy input to CHP station}} = \frac{1 + R}{(1 + RZ)} \eta_e \text{ per cent}$$

Since $Z < 1$, then clearly $\eta_e (1 + R)/(1 + RZ)$ is greater than η_e.

However, this is not a very useful or meaningful exercise since the outputs of the CHP station and of the power station are not similar. The two products, electricity and heat, have different values thermodynamically and economically. The case for the 'improved efficiency' of CHP can be put on firmer ground by comparing the inputs required by the three conversion processes to achieve the same effect.

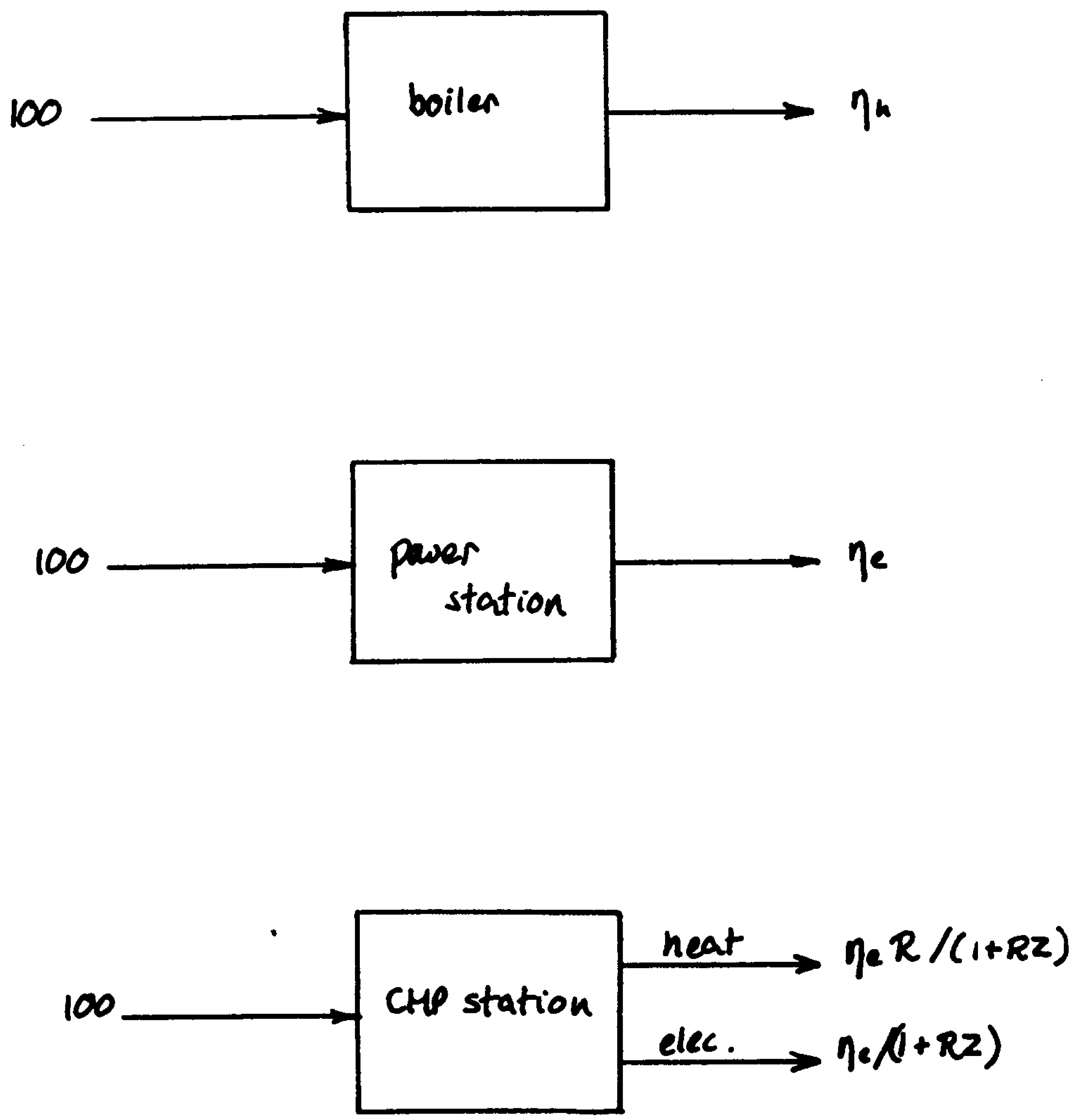


Figure A.10.1 Comparison of output from boiler, power station and CHP plant

If for the moment, we ignore the purposes for which heat and electricity are used, then electricity production capacity 'lost' by the substitution of CHP stations for conventional power stations can be made up by CHP plant with additional fuel burning capacity. The power station of Figure A.10.1 can be replaced by CHP plant burning 100(1 + RZ) of fuel (Figure A.10.2) tn produce η_e units of electricity and $\eta_e R$ units of heat. On the basis of this comparison, the CHP station has, by the burning of 100RZ units of fuel, produced $\eta_e R$ units of heat, in addition to the 'normal' electricity generation. Energy savings will result from the use of CHP, provided that the ratio of heat production $\eta_e R$ to 'additional' fuel burned, 100 RZ, is greater than the efficiency of the heater $\eta_h/100$. This will be the case as long as $\eta_e/\eta_h > Z$. Indeed the condition that Z is less than the ratio of the efficiencies of the existing power stations and heaters is the minimum justification for the adoption of CHP. This condition for positive energy savings can also be demonstrated by adopting the conventional heater as the standard of reference and comparing the generation efficiency of the electricity 'by product' with conventional generation.

·Specific energy savings

The absolute magnitude of the energy savings will, of course, depend upon the extent to which present power station and heater capacity is replaced by CHP plant. It is useful therefore to express energy savings in terms of energy saved per unit capacity replaced. These 'specific energy savings' can be determined quite easily as shown below.

In this case electricity production capacity of η_e units is replaced by CHP electricity capacity of η_e. Since it takes 100 units of fuel to produce $\eta_e/(1 + RZ)$ units of electricity, the replacement CHP capacity

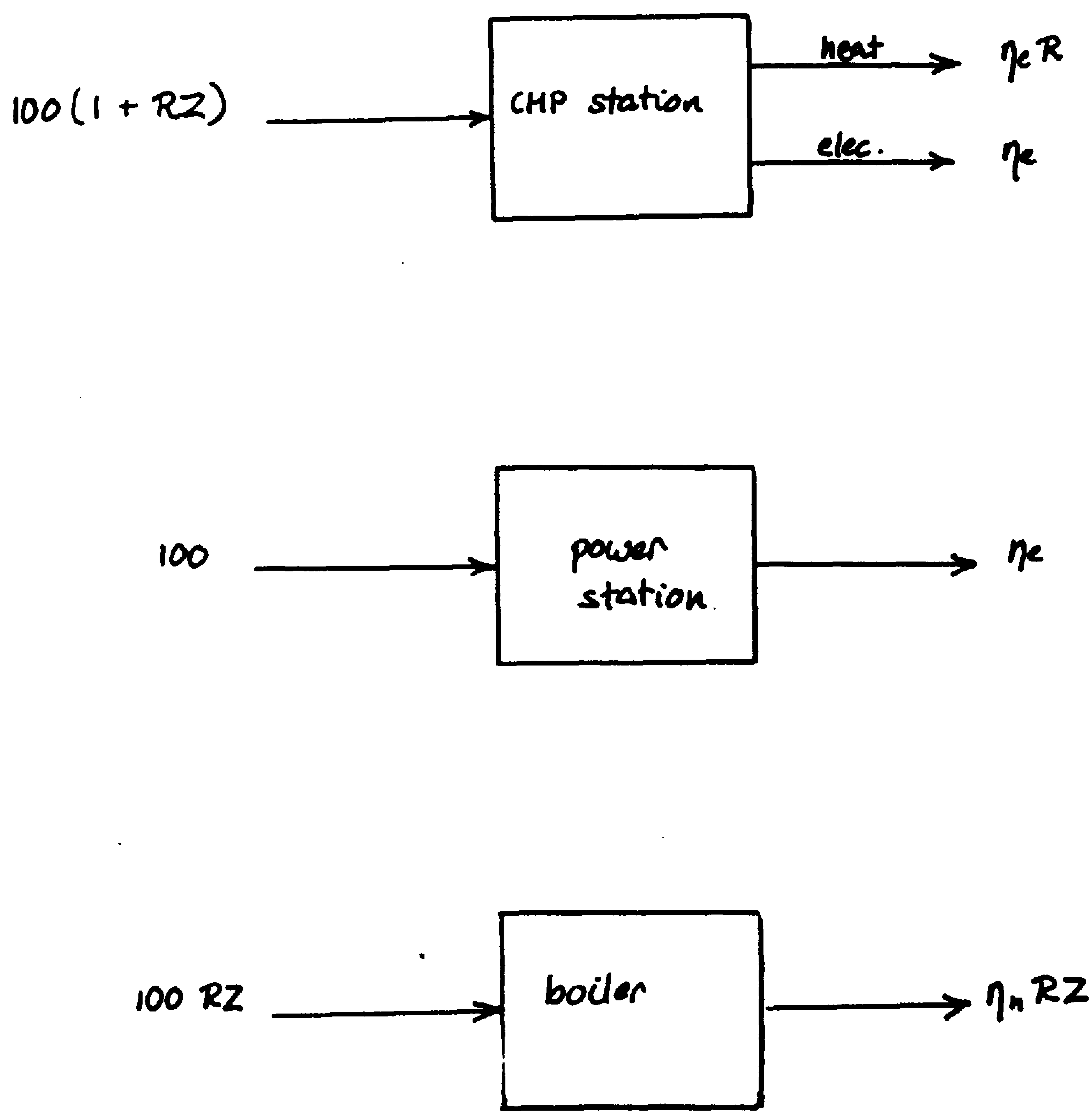


Figure A.10.2 CHP station output in terms of Z must burn 100 (1 + RZ) units of fuel to produce these η_e units of electricity. Under this convertion, 100 of these units of fuel can be attributed to the production of electricity. The remaining 100RZ units can be attributed to the production of $\eta_e R$ units of heat.

Using conventional heaters, the production of η_h units of heat requires the combustion of 100 units of fuel. So the production of $\eta_e R$ units of heat by the CHP plant will displace heating plant that would consume 100 $\eta_e R/\eta_h$ units of fuel. The net energy savings arising from the replacement of η_e units of electricity capacity will be the difference between the 100 $\eta_e R/\eta_h$ units that would be burned in the conventional heater and the 100 RZ units of fuel attributable to the production of heat in the CHP station; in other words, $\frac{100R}{\eta_e}\left(\frac{\eta_e}{\eta_h} - Z\right)$ units of fuel per unit of electricity production replaced.

Energy saved per unit of heating capacity replaced.

The method of calculating the specific energy savings under this convention is exactly analogous to the previous case.

Fuel required by CHP statio to produce η_h units of heat = $\frac{100(1 + RZ)}{R\eta_e}\eta_h$

Fuel attributable to heat production = 100 units.

∴ Fuel attributable to electricity production $\frac{100(1 + RZ)\eta_h}{R\eta_e} - 100$

Electricity produced by CHP plant producing η_h units of heat = η_h/R

Fuel required by power station to produce η_h/R units of electricity

$$= \frac{100}{\eta_e}\frac{\eta_h}{R}$$

$$\text{fuel saved} = \frac{100}{\eta_e}\frac{\eta_h}{R} - \frac{(100(1 + RZ)\eta_h - 100)}{R\eta_e}$$

$$= 100\ \frac{\eta_h}{\eta_e}\quad\frac{\eta_e}{\eta_h} - Z$$

fuel saved per unit of heating capacity replaced

$$= \frac{100}{\eta_e}\left(\frac{\eta_e}{\eta_h} - Z\right)$$

Comparison of efficiency

Since the two products of CHP are not alike, the calculation of overall efficiency of CHP stations is not a very helpful activity. The folly of this is illustrated by the observation that the efficiency of some heating plant is frequently higher than that of CHP stations. Indeed, if efficiency were the only criterion of energy conversion, then power stations would not be either necessary or desirable. The point is, of course, that the 'quality' of the energy arising from an energy conversion is as important as the quantity.

However, it is possible to compare the efficiency of CHP plant with equivalent power stations and heating plant, while avoiding this difficulty.

CHP plant will produce R times as much heat as electricity. The fuel input to the CHP plant can be allocated to the production of each product can be made on the basis of the quantity of fuel required to replace the product by conventional heaters or a power station.

R units of heat can be produced in a heater by the combustion of $100R/\eta_h$ units of fuel. 1 unit of electricity can be produced in a power station by the combustion of $100/\eta_e$ units of fuel. We can define one 'combined unit' of output from a power station as consisting of R units of heat and one unit of electricity. The one 'combined unit' of output can be produced by the separate power station and heater by the combustion of $(100R/\eta_h + 100/\eta_e)$ units of fuel. The proportion used for electricity production is $\eta_h/(R\eta_e + \eta_h)$ and for heat production, $R\eta_e/(R\eta_e + \eta_h)$. These proportions can be used to allocate the proportions of fuel consumption allocatable to each of the products in the case of the CHP plant.

In a CHP plant burning 100 units of fuel to produce $_eR/(1 + RZ)$ units of heat and $\eta_e/(1 + RZ)$ units of electricity, the quantity of fuel allocated to heat production is $100\ R\eta_e/(R\eta_e + \eta_h)$.

The efficiency of production of each of the two products can be calculated.

Efficiency of heat production in CHP plant

$$= \frac{\eta_e R/(1 + RZ)}{100\ R\eta_e/(R\eta_e + \eta_h)}$$

$$= \frac{\eta_h}{100} \quad \frac{1 + R\eta_e/\eta_h}{1 + RZ}$$

Efficiency of electricity production in CHP plant

$$= \frac{\eta_e/(1 + RZ)}{100\ \eta_h/(R\eta_e + \eta_h)}$$

$$= \frac{\eta e}{100} \quad \frac{1 + R\eta_e/\eta_h}{1 + RZ}$$

It has been shown previously that the minimum requirement for an energy saving CHP project is than $\eta_e/\eta_h > Z$. It can thus be seen that if this condition pertains then the 'partial' efficiencies of heat production and of electricity production in CHP plant is <u>greater</u> than the efficiencies of the separate plant.

Conclusions

There are a wide variety of ways in which the energy savings arising from the adoption of CHP technologies can be evaluated; some of them more helpful than others.

A minimum condition, $\eta_e/\eta_h > Z$, exists for which CHP will save energy compared with the equivalent separate plant.

Efficiency of CHP plant can only be compared with that of separate plant if some means of allocating fuel input is used. Under the allocation rule used here, the efficiency of both productions is shown to be greater than that of separate plant.

APPENDIX 11

Notation

Throughout this thesis, vectors are denoted by lower case letters and matrices by upper case letters. A prime is used to denote transposition and a circumflex over a vector denotes a vector transformed into a diagonal matrix. Unit vectors are denoted by i and identity matrices by I.

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A make matrix: elements a_{ij} represent quantity of commodity i produced by industry or process j

B absorption matrix: elements b_{ij} represent quantity of commodity i purchased by industry or process j

q total production vector: q_i is the total quantity of commodity i produced by the economy

f final demand vector: f_i is the quantity of commodity i purchased by final demand

g industry output vector: g_j is the sum of the outputs a_{ij} from industry j

P product mix matrix; p_{ij} is the proportion of industry j's output accounted for by its production of commodity i

R input mix matrix: r_{ij} is the quantity of commodity i purchased by industry j per unit total output from industry j

D market share matrix: d_{ij} is the proportion of the whole economy's output of commodity j which is contributed by industry i.

X technical coefficient matrix; x_{ij} is the input i required as input to the production of one unit of j. X may be calculated using either industry or commodity technology assumptions

I identity matrix

i unit vector : (May be a row or column vector)

M matrix of intensity

v import flag vector

y total imports vector

x vector of process activity levels

E matrix of residuals

C absorption from imports matrix: elements c_{ij} represent quantity of imported commodity i purchased by industry or process j

u vector of imports

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